

A GEIGER COUNTER STUDY

OF THE

COSMIC RADIATION

Thesis by

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SUMMARY.

A discussion of the development of the Geiger counter as applied to cosmic rays is given. The development of coincidence selecting circuits is particularly emphasised and various types of circuits are described in detail.

Experiments dealing with the coincidences observed between three counters separated by considerable thicknesses of lead are shown to offer evidence that such coincidences are for the most part caused by the passage of single particles in straight lines through the counters and the intervening lead. Perhaps 10% of the coincidences arise from secondary particles operating at least one of the counters.

Several types of shower experiment are described and an analysis of the curves obtained is made. This leads to an estimate of the rates of absorption of the shower producing radiation and the shower particles. Further experiments give information as to the nature of this radiation and of the showers themselves.

Experiments on the variation of the showers with altitude and latitude are also described. These show that although the showers are softer than the general radiation they suffer a smaller latitude effect.

CONTENTS.

I. Historical Introduction	1
II. Construction of the Geiger Counter	5
III. Operation of the Counter	8
IV. Coincidence Circuits	12
V. Applications of the Geiger Counter	
to Cosmic Ray Investigations	22
VI. An experiment with a Cosmic ray	
Telescope	24
VII. Experiments involving the Penetrating	
Part of the Radiation	27
VIII. Experiments in the Shower Phenomena	36
IX. The Altitude Variation of the Showers	64
X. The Geographical Variation of the Showers	66
XI. Conclusions	72

I. HISTORICAL INTRODUCTION

In the year 1928 Geiger and Muller⁽¹⁾ first reported a new, more sensitive detector of ionising radiation. This was an adaptation of the Geiger point counter, and, for obvious reasons was called the tube counter. The tube counter was more sensitive than the old point counter because of its much larger sensitive volume, and this meant that the new counter could be used to detect the cosmic radiation.

In the first work with the new counter the passage of radiation through the counter was evidenced by connecting the counter to a source of high potential and then detecting the current that occurred as a consequence of the passage of an ionising particle by noting the kick of some sort of electrometer connected in the circuit. For quantitative work these kicks were recorded photographically on a moving film and hence the number of particles that passed through the counter in a given time could be found. Using this procedure Geiger and Muller⁽¹⁾ found that the counting rate of their counter when responding only to the natural radiation present in a room was indeed decreased when a shield of 60 cms. of iron was put above the counter.

Bothe and Kolhorster⁽²⁾ then devised a means of using the counter to detect the presence of very penetrating particles in the cosmic radiation. To do this they set up two counters in a vertical plane and recorded the kicks from the counters

side by side on the moving film. By inspection of the film they found how often coincident discharges had occurred. The frequency of these coincidences was far too large to be accounted for by chance alone and hence they concluded that single ionising particles were passing through the two counters. By putting blocks of lead and gold between the two counters they found a decrease in the rate of coincidences and hence they were able to measure the absorption of the penetrating particles. The rate of absorption was found to be of the same order of magnitude as that of the total cosmic radiation as measured by lowering an electroscope into water.

Shortly after this time a number of vacuum tube circuits were developed to record the pulses from Geiger counters and particularly to record the coincident impulses from two or more counters. The most important circuit is undoubtedly that due to Rossi⁽³⁾ and today I think it safe to say that everyone who uses counters is also using Rossi's method to detect coincidences. In 1933 Rossi⁽⁴⁾ published the first extensive paper containing results of coincidence measurements. He used three counters and thus was able to reduce his accidental coincidences so low as to be able to detect very small effects. Thus he was able to show that coincidences could be obtained when as much as a meter of lead was between his counters. He also found that groups of particles on widely divergent paths occurred beneath thin plates of lead and iron.

This paper attracted a great deal of attention and many

experimenters began using Geiger counters in cosmic ray investigations. The method of coincidences obviously offers many advantages in fields that are difficult or impossible for the electroscope. For example the counters can be so arranged as to respond only to those rays that come from a given direction. Then too the whole field of shower phenomena and secondary particles in general can be easily investigated with counters. Recently counters have been used with the cloud chamber to make the operation automatic and thus to help greatly in the accumulation of data.

An important disadvantage of the coincidence method is that in most cases the number of coincidences recorded per hour is of the order of a few tens and hence because of statistical fluctuations readings must be taken for many hours to get a small probable error. If it be assumed that the probable error is the reciprocal of the square root of the number of counts recorded then 10,000 counts are needed for 1% accuracy. This requires that the counters and the electrical circuits keep constant over long periods of time. Another disadvantage is in the counters themselves. At least with our present techniques the rate at which the counter registers is dependent on the voltage on the counter and the constants of the associated electrical circuit as well as the number of ionising particles present. This means that it is difficult for the counter methods to give accurate quantitative results for measurements of such quantities as the number of ionising

particles passing through the counter in unit time. However, provided that experiments are devised that compare counting rates with different arrangements of matter near the counters then clearly it will be possible to give the effect of the new arrangement as a percentage change from the first arrangement. This percentage will be genuine provided that there is no change in the efficiency of the counters during the experiment. To test this point the counting rate with the first experimental set up should be checked at the end of the experiment. Still another factor leading to errors with coincidence experiments is the presence of a "background" count due to accidental or chance coincidences. The number of these will depend on the counting rates of the individual counters and so may change with the changing conditions of the experiment. The only satisfactory way of eliminating this error is that of removing the cause as far as possible. This can be done by improving the coincidence selecting circuit or by increasing the number of counters. If the accidental coincidences are a small fraction of the real coincidences then they may be neglected.

The above considerations indicate that care must be taken in interpreting the results of coincidence experiments and perhaps they help to explain why so many apparently conflicting results are published.

II. CONSTRUCTION OF THE GEIGER COUNTER

When Geiger first gave instructions for the construction of the tube counter he was careful to insist that the central wire was the most important part of the counter. The tube could be of any kind of metal but the central wire should be of iron with a carefully prepared oxide film. The purpose of the oxide coat was to prevent the incipient discharge from becoming a stable arc and also to extinguish the discharge. Clearly since the field strength is a maximum at the surface of the wire, it is necessary that this surface be as smooth as possible.

It was soon found that at least with the vacuum tube circuits used for registering counter impulses the semi-insulating oxide film was unnecessary as the circuit itself limited and extinguished the discharge. However, apart from this fact each worker tended to develop his own formula for the construction of his counters, and indeed Hummel in Germany was moved to sum the situation with: "To make good counters one must not only read all the literature and spend a few months experimenting, but also be born lucky and have a lucky godfather".

The first serious effort to determine what makes a good counter came from Curtis⁽⁵⁾ in Washington. He tried a great many different wires and cylinders and concluded that the surface of the cylinder rather than the wire was the critical surface.

The first counters made here at the institute were of brass as was the common European custom. However these would not count except by using an artifice recommended by Curtis. This consisted in coating the surface of the cylinder with soot. The counters were still not very satisfactory. Copper cylinders were then tried and good counters were finally made. In agreement with Curtis it was found that the wire was not critical. Central wires of copper chromel and tungsten all worked without any special treatment, and there is no reason to believe that this list exhausts the possible wires. The diameter of the wire affects the operating voltage slightly but is not critical. There is some evidence that counters made with larger wires, 20 mils and thicker, have a longer plateau on the count versus voltage curve. The inside surface of the cylinder is made as smooth as possible. The cylinder is then heated to remove traces of grease and to leave a thin oxide coat on the surface. If the counter is now assembled there is a fair chance that a good counter will result. Recently however, it has been found that treating the assembled counter with dilute nitric acid and then washing with distilled water and immediately evacuating will almost certainly guarantee a good counter.

To fill the counter clean dry air at something over 5 cms. pressure is usually used. If a mixture of air and argon is used the operating voltage will be considerably lowered. Strangely enough pure argon is not satisfactory,

there must be at least 20% air in the mixture before the counter will be sensitive.

At first the counters were not sealed in glass but merely closed with hard rubber plugs. These of course leaked slowly and hence were kept on a constant pressure system. In spite of this constant leak of fresh air these counters worked well for many months.

The present counters are of one inch external diameter hard drawn copper tubing about 1.5 mm. thick and 14 cms. long. They are sealed in glass with 20 mil tungsten for the central wire.

III. OPERATION OF THE COUNTER

As previously stated, the first counters were used by connecting a suitable source of high potential to the counter and detecting the pulses of current that occurred when an ionising particle passed through the counter by some sort of electrometer. By this means it was established that if one plotted a curve of counting rate as a function of counter voltage, one found that below a certain threshold voltage no counts were registered. A few volts above the threshold the rate had increased rapidly to a certain value. For the next hundred or more volts the curve was nearly horizontal. A further increase in voltage caused a rapid increase in counting rate, until finally the counter broke down and a glow discharge occurred. The flat part of this curve, the "plateau", was taken as being the true counting rate for the counter.

A more convenient way of recording counter pulses is to use a vacuum tube circuit, (Fig. 1), and then to take the amplified pulse and use it to operate any sort of electrical device desired. It is perhaps worth noting that with this circuit a grid swing of about 10 volts will be obtained at the first tube. This is ample to give a good output without any special precautions in the construction of the amplifier. With such a circuit the counts versus voltage curve is as described above, however, if curves are plotted using the resistance R as parameter, it will be found that the lower the value of R the shorter the plateau, and the greater the

counting rate for a given voltage. If one listens to these rapid counts with a loudspeaker it is apparent that they come in bursts, that is, one count seems to give rise to others which gradually become fainter.

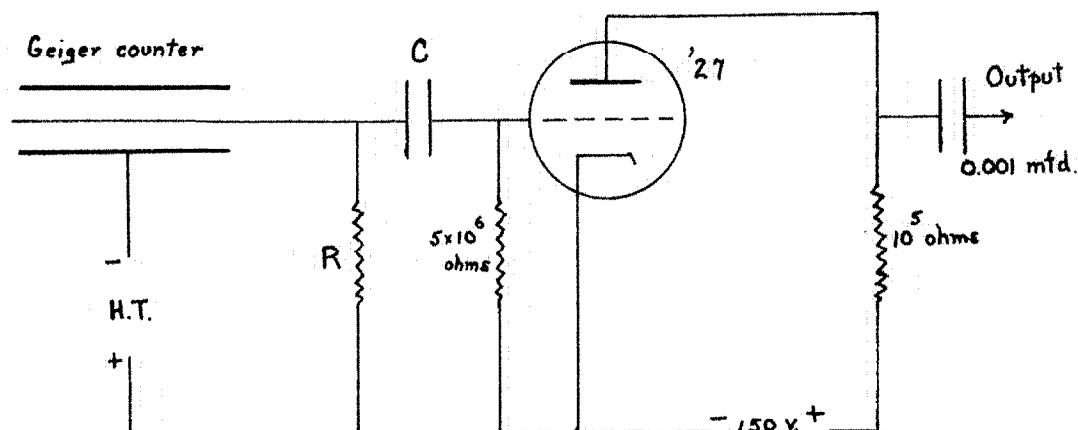


Fig. 1

The operation of the counter may be described qualitatively as follows. When the field in the counter is sufficiently high the ions released by the passage of an ionising particle move to the walls and wire with sufficient energy to cause cumulative ionisation. In a very short time there are sufficient ions present to support a large flow of current, and, if the voltage across the counter were maintained at its original value a stable discharge would set in. The existence of this discharge can be readily demonstrated experimentally. It turns out that it is of the constant voltage type with a voltage about equal to the threshold voltage of the counter.

The discharge is stable when a current of a very few microamps is flowing. For a practical counting circuit it is clear that some means must be used to prevent the discharge current from becoming too large and to extinguish it in the shortest possible time. It is easy to see how this is accomplished with the circuit shown in Figure 1. As the counter draws current from the high tension supply the condenser C becomes charged. In a short time C has reached a high enough potential to lower the voltage across the counter to the threshold value. The resistance R is so high that insufficient current to maintain the counter discharge can flow through it. Hence the discharge must stop and C at once begins to discharge through R. When this is complete the counter is ready to receive another particle. Usual values for R and C are 10^9 ohms and 5×10^{-11} farads.

Consider the effect of gradually increasing the voltage across the counter. Nothing will happen until the threshold voltage is reached. This presumably is the voltage at which cumulative ionisation sets in. It will depend on the kind of gas present and the gas pressure. It will also vary with the physical dimensions of the counter because of the necessity of having a certain field strength. The field strength at the surface of the wire is clearly a maximum and is given by the expression: $E = V/r_1 \log_e(r_2/r_1)$ where V is the potential across the counter and r_1 and r_2 are the radii of the wire and cylinder respectively. In a practical case r_2/r_1

will be about 50 so that it is easy to see that to maintain the field strength at the surface of the wire constant the potential applied to the counter must vary nearly as the radius of the wire. Although no accurate experimental data on this question is available there is no doubt that the threshold voltage of the counter does not show any such dependence upon the radius of the wire. This means that the threshold voltage must be determined by the average or perhaps the minimum field rather than the maximum.

As the counter voltage is increased the counting rate shows a rapid increase. This first increase is due to the fact that at first the impulses are not large enough to operate the amplifier but the change of a few volts in the operating potential is sufficient to make all the pulses register. Another cause for an increase is that at the higher voltage a larger percentage of the counter volume is sensitive. Obviously when both these effects are completed the counting rate should remain constant with a further increase of voltage. This is the case until the voltage becomes so high that the current which can flow through R becomes almost enough to maintain the discharge, and hence to cause an instability after each pulse. Such instability can also arise from too high field strengths at small irregularities on the surface of the wire.

This description of the operation of the counter is necessarily incomplete. For example nothing has been said about the reason for a smooth surface on the cylinder or for using a mixture of air and argon rather than pure argon.

IV. COINCIDENCE CIRCUITS

To record coincident discharges of two or more Geiger counters it is necessary to do two things. First, the counter pulses must all be made the same size and shape, and second, an electrical counting circuit must be devised that will recognize the arrival of simultaneous pulses. The reason for the second criterion is obvious, however the first is just as important. If for example the pulses varied in magnitude, then a pulse of twice the average size would be mistaken for a coincidence. Again, if some of the pulses were longer than others then two long pulses occurring a time interval apart equal to their length would be registered as a coincidence.

The value of a coincidence circuit will depend on two further criteria. First, the resolving time of the circuit and second, the ability of the circuit to register all the coincidences. By resolving time of the circuit is meant the maximum time by which two impulses may be separated and still be recorded as a coincidence. If a circuit is to be of any value this time must be at least as short as the original pulse and preferably some means should be taken to shorten it still further. The resolving time of a double coincidence circuit may be found experimentally by connecting two counters to the circuit while the counters are separated as far as possible in a horizontal plane. The coincidences then observed will depend only on the resolving time of the circuit and the individual

counting rates of the two counters. According to the theory of probability the coincidence rate is given by: $2 N_1 N_2 t$ where N_1 and N_2 are the individual counting rates and t is the resolving time. In any experiment involving double coincidences this number should obviously be subtracted from the observed number of coincidences to give the true number of coincidences due to the radiation passing simultaneously through the counters. The second criterion is important because for the above reason the output pulse must be very short and hence any small variation in this pulse may mean that the adding part of the circuit may fail to recognize the occurrence of a coincidence. As the efficiency of the circuit is increased by decreasing the resolving time, this second trouble becomes increasingly apparent.

The first coincidence selecting device was due to Bothe and Kolhorster.⁽²⁾ Their method was to record the pulses on a moving film and then by visual inspection to determine how many coincidences had occurred. This is laborious and expensive and almost out of the question for any extended observations. There is also the trouble that the resolving time is excessively long unless the film is moving very rapidly.

The next suggestion was to use a vacuum tube with two grids. Impulses from the two counters would be fed on to these grids but no great change in the plate current could occur unless the two grids received simultaneous pulses. This method is fairly satisfactory but it is difficult to extend it

to triple coincidence recording without undue complications. Another difficulty is that the two grids are not symmetrical in their action and a large pulse on the most sensitive grid may be recorded as a coincidence.

Hummel⁽⁶⁾ then published a circuit which appeared very ingenious. His method was to connect the two counters in series in such a way that there was insufficient voltage on one counter unless the other counter was receiving an impulse. Hence the first counter registered only the coincidences. This circuit was tried by the writer but was found to be impracticable.

In 1930 Rossi,⁽³⁾ in a short note in Nature, presented the circuit shown below (Fig. 2). This circuit operates as follows.

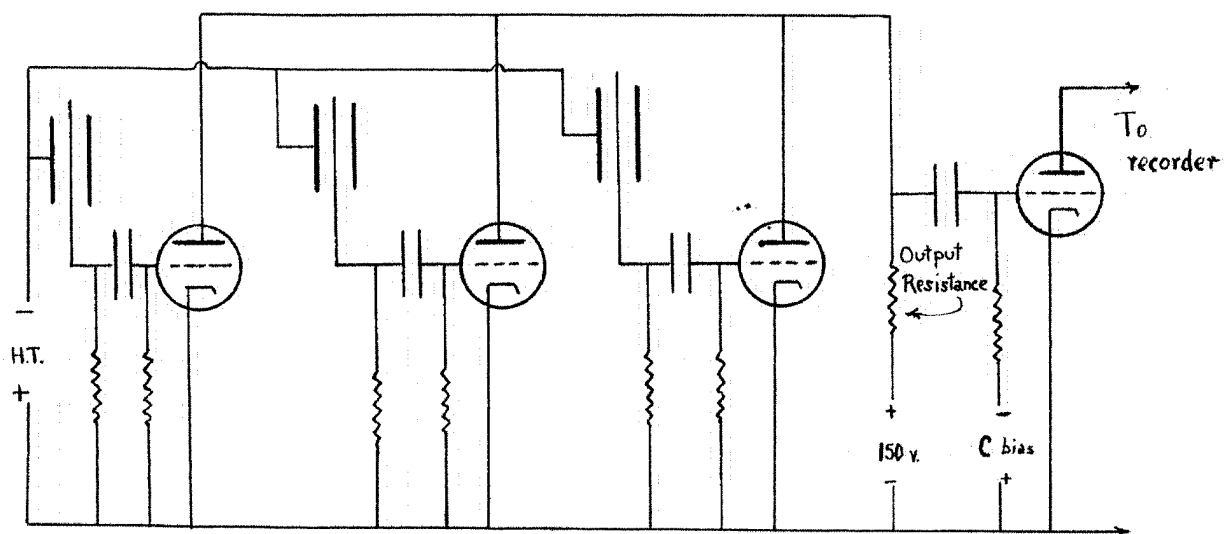


Fig. 2

An impulse from any counter causes the grid of the corresponding vacuum tube to go negative for an instant. Hence the plate current in this tube drops almost to zero. This decrease in the total plate current causes a similar change in the

potential across the output resistance. The following tube is so biased that no current flows unless the grid is given an impulse equal to the total drop in potential across the output resistance. This can only occur when all the counters receive simultaneous impulses.

In this, its original form, the circuit is not yet entirely satisfactory. For example, if it is to be used with three or more counters then it is clear that unless the bias conditions on the output tube are very carefully adjusted there is a danger that a coincidence between all the counters but one will be recorded as a real coincidence. Another difficulty lies in the fact that the Geiger counter does not produce pulses of regular size, and hence a small pulse may not completely cut off the plate current in the first vacuum tube. Under these conditions a real coincidence will not be registered.

In an effort to avoid these troubles a coincidence recording circuit was devised that used the characteristic of the thyatron type of tube. These tubes contain mercury vapor and a suitable pulse on the grid will cause an arc to form inside the tube. The current that flows depends only on the characteristics of the external circuit and once the arc has started the grid loses all control. It is clear that if a thyatron is triggered off by the pulse from a Geiger counter the current that flows in the thyatron circuit will be independent of the size of the counter pulse provided only that

this exceeds a certain minimum. If now these current pulses of fixed magnitude are collected and sent down a common resistance, then the voltage drop across this resistance will be strictly proportional to the number of counter pulses that occur simultaneously. This voltage drop is applied to the grid of another thyatron, and again the trigger action of the thyatron assures that no current shall flow until the voltage exceeds a certain predetermined maximum. This output current is made to operate a mechanical counter. The complete circuit is shown in Figure 3.

This circuit was found to be more successful than Kossi's, but had several disadvantages. In the first place, from a practical point of view, it was expensive to build because of the number of thyatrons required. This trouble was partially removed with the appearance of the argon filled tubes on the market. Another difficulty is that the current in the thyatrons must be interrupted in some way to restore them to a sensitive condition. This can be done with a relay as shown in Figure 3 or by means of the circuit of Figure 4. If a relay is used the resolving time of the circuit depends on the time taken for the relay to open, and also the circuit is dead for the time that the relay remains open. By building a relay of the moving coil type it was found possible to reduce the resolving time to about 10^{-3} seconds. The relay was probably open for a longer time than this but with counters counting at a rate of less than 100 per minute the probability of two counts within say 1/100 second of each other is very small and

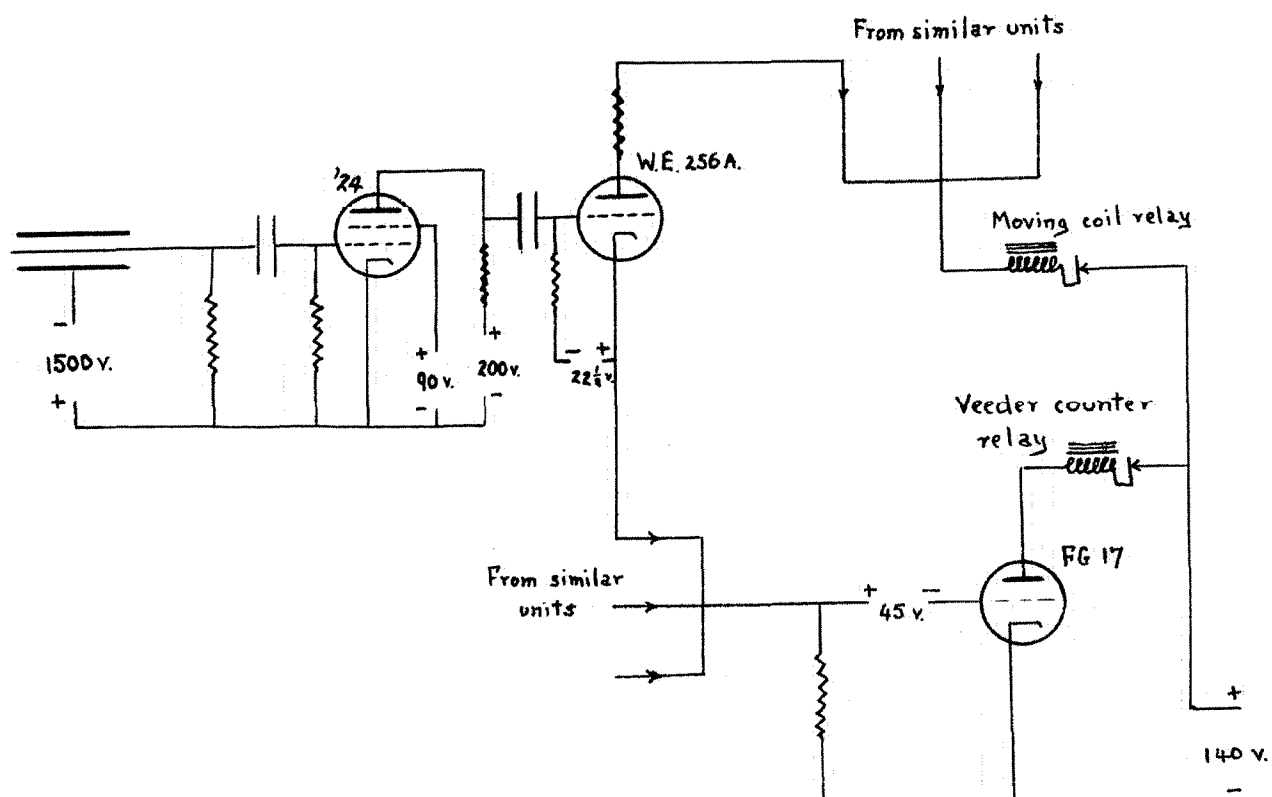


Fig. 3

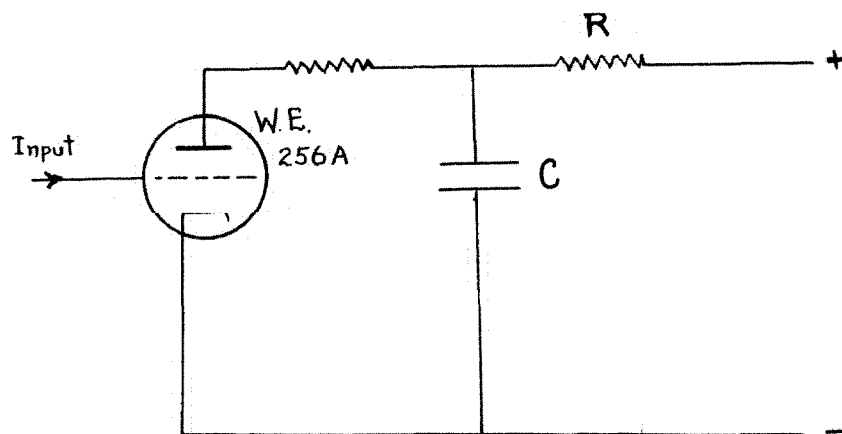


Fig. 4

hence the counts lost should be correspondingly small. With the method of Figure 4 there are no moving mechanical parts to cause trouble and the resolving time depends on the electrical constants of the circuit. This circuit operates as follows. When the thyatron becomes conducting the condenser C discharges through the tube. This means that the current in the tube decreases exponentially to a minimum fixed by R. If R is large enough this minimum will be too small to maintain the arc and hence if the grid is again negative the current will stop and the grid regain control. C immediately begins to recharge, and in a time determined by the product RC the tube is ready to receive another impulse. This circuit was found to be more satisfactory than that using the relay and a resolving time about one fifth of the original value was obtained.

Although at first sight it appears easy to extend this circuit to record coincidences between any number of counters, a closer investigation shows that even with three counters the greatest possible voltage difference across the output resistance between a double and a triple coincidence is only 10% of the line voltage. Although this is not too small to register on the output thyatron it is getting near the limits of reliable operation, and a very slight change in the shape of one of the pulses will cause a coincidence to be missed. Because of this the circuit of Figure 4 is not reliable for triple coincidences and the relay must be used. However this is not a serious difficulty because with triple coincidences the number of accidental coincidences is very small.

Within the last few years several new types of vacuum tube have appeared on the market and, as first pointed out by Johnson⁽⁷⁾ and his co-workers at the Franklin Institute, tubes are now available to make the Rossi circuit much more satisfactory. This amended Rossi circuit is now used here (Fig. 5). The pentode tubes used in the first stage are the essential difference between this and the original circuit. If the plate current in these tubes is plotted against the grid voltage it will be found that the current cuts off very sharply when the grid is about 4 volts negative. In the counter circuit the counter pulses are always larger than this and hence every pulse completely stops the plate current. The pentodes possess another advantage that is best illustrated by an actual example. In this case triple coincidences were being recorded, and about 120 volts plate supply was used. When no pulses were present the voltage across the output resistance was about 100 volts. If a single pulse occurred it would be expected that this voltage would change to about $2/3$ of its original value. Actually a change of about 1 volt occurred. The explanation is that under these conditions the pentode acts as a constant voltage device and as current stops in one tube and the voltage across the other tubes begins to rise these take more current and keep the resultant current about constant. When two tubes stopped drawing current the change in output voltage was still only about 10 volts. When all three stopped the change was of course 100 volts. This demonstrates clearly

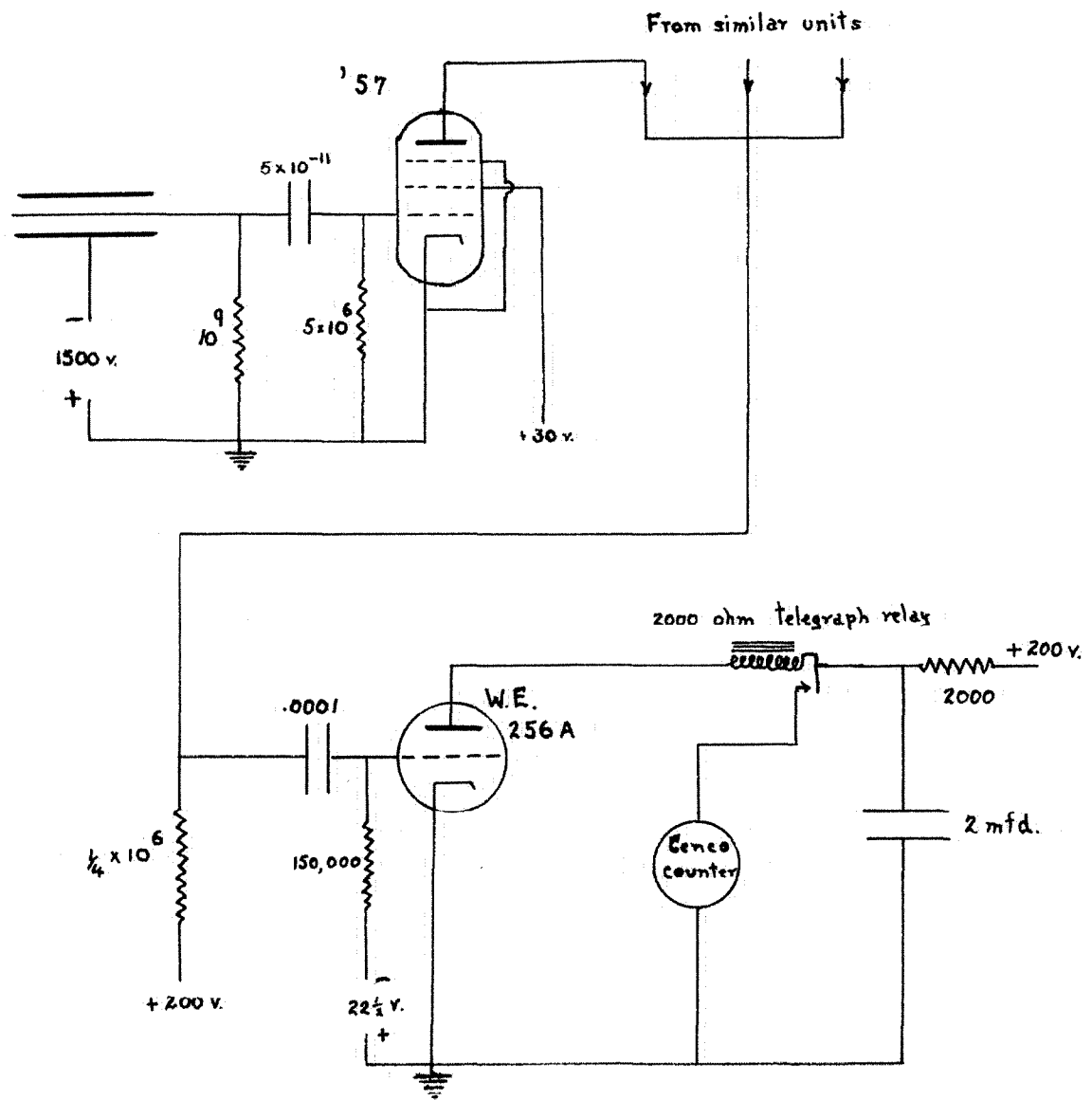


Fig. 5

the fact that the pentode tubes give a circuit with which there is no doubt as to the occurrence of a coincidence.

To record the coincidences an argon type thyratron is used. In the plate circuit is a telegraph relay that operates a Cenco impulse counter. With this arrangement about 1000 random impulses per minute can be counted with the telegraph relay the limiting factor. It will be noted that the current for the Cenco counter is taken from the plate supply so that the circuit is readily adapted to a portable form.

With this circuit the resolving time depends upon the length of the pulse from the Geiger counter itself. This, in general will be somewhat longer than desirable. To remedy this defect a three stage resistance coupled amplifier can be used with each counter. By choosing suitable values for the coupling capacities and resistances, it is possible to shorten the output pulse by any desired amount. Three stages are necessary to give an output pulse in the right direction.

This modification of the Rossi circuit has the advantages of simplicity, accuracy, versatility, (Johnson reports that as many as ten counters could be used if desired), and, with the three stage amplifier, of a resolving time as low as desired. There is no doubt that this method of recording coincidences is the most satisfactory yet devised.

V. APPLICATIONS OF THE GEIGER COUNTER TO COSMIC RAY INVESTIGATIONS

The Geiger counter naturally lends itself to the investigation of several different types of problem. These may be listed as follows.

(a) Directional effects.

When two or more counters are arranged with their axes parallel and with no great amount of material between them, the coincident discharges of these counters must be due to the passage of a single ionising particle through the set of counters. Such a counter train responds only to rays from a certain solid angle and hence can be used to investigate the distribution in direction of the corpuscular part of the cosmic radiation.

(b) The properties of the penetrating particles associated with the cosmic radiation.

If a counter train is set up with a large amount of material between the counters coincidences are still observed. It will be shown that the evidence is in favor of most of these coincidences being caused by the passage of a single particle through the counters and the intervening matter.

(c) The cosmic ray showers.

If three counters are set at the corners of a triangle beneath a thin plate of lead or other heavy material coincidences are observed. These in general must be due to

at least three separate ionising particles emerging from some point in the lead and travelling on widely divergent paths.

(d) The automatic cloud chamber.

Coincident discharges of two or more counters are made to operate a cloud chamber near the counters.

(e) The geographical distribution.

Besides these specialised fields the Geiger counter may also be used in much the same way as the electroscope to investigate such matters as the geographical distribution of the radiation. For this type of problem the counters are put as close together as possible so that rays from as large a solid angle as possible will register. It might be noted in passing that the counter is not as convenient as the electroscope because of the greater complexity of its electrical circuits and because of the temperamental nature of the Geiger counter itself.

VI. AN EXPERIMENT WITH A COSMIC

RAY TELESCOPE

Directional counter trains have been used to measure the intensity of the radiation at different angles with the vertical and in this way the east west asymmetry was discovered and investigated, but as yet no experiments have been reported that attempt to detect differences in the intensity of the radiation coming from the direction of any of the heavenly bodies. In the early part of 1933 the writer and B. O. Sparks attempted to compare the radiation coming from the direction of the sun with that in its vicinity but it was soon apparent that with the equipment then available the task was impossible. When the counters were separated sufficiently to subtend a solid angle comparable to that of the sun, the number of coincidences was so small as to be indistinguishable from the background of chance coincidences. The only way in which this experiment could succeed, would be to use counters much larger than those ordinarily found. In this case it would also be necessary to use four counters to decrease the accidental counts.

Another attempt to measure the effect of an extra terrestrial body on the radiation was made in 1935. This time measurements were made on a region near the constellation of Cygnus. According to the astronomers the region is occupied by a large mass of obscuring matter several degrees in extent,

and hence it would be expected that if the corpuscular part of the radiation travelled in a straight line or if the corpuscles observed at the surface of the earth were secondaries from incoming photons that were emitted in nearly the same direction as the primary, then a counter train directed at this region would register fewer coincidences than if the train was directed at a point near the region.

To test this point a small polar axis was built with a synchronous motor drive. A time switch was provided to start and stop the motor. The counters were mounted on an axis that could be set in declination. The distance between the counters was such that they subtended a solid angle of 5 by 15 degrees and the long axis of the counters was so oriented as to be parallel to the long axis of the obscuring matter. Runs were taken for eight hours, four hours each side of the meridian. These were alternately directed at the center of the region and at points having the same declination but differing by at least two hours in right ascension. The result of a series lasting over about six weeks was that within the limits of error, about 5%, the rate on the region was the same as that outside of the region. There was also some slight evidence that the intensity two hours east of the region was less than that from the region.

To increase the accuracy of this experiment it is necessary to have more counts. This could be done in three ways: The counters could be made larger, the experiment could be

performed at a high altitude, and the experiment could be carried on for a longer time. This last remedy is not very satisfactory in itself alone because of loss of sensitivity of the counters and troubles in the electrical circuit that are bound to develop after some time of continuous operation, but in connection with the other two remedies it is believed that it is quite feasible to get an accuracy of better than 1%. However if solid angles much smaller than the above are used it will be a long and tedious matter to measure the absorption with any such accuracy.

VII. EXPERIMENTS INVOLVING THE PENETRATING PART OF THE RADIATION.

After the original experiments of Bothe and Kolhorster had shown the existence of radiation that could cause coincidences between counters placed above and below thick plates of matter, Rossi⁽⁴⁾ in 1933 reported at some length on a series of experiments that are of prime importance in a study of this phase of the subject. Three counters were set up so that coincidences could be observed with 25 cms. of lead between the counters and with 101 cms. of lead between. The incoming radiation was first filtered through 7 cms. of lead. He found that real coincidences were indeed observed with the 101 cms. of lead between the counters and furthermore, that the decrease in the number of coincidences in going from 25 cms. to 101 cms. of lead about corresponded to the decrease in ionisation as measured with an electroscope that was placed beneath a corresponding mass of water. To insure that the coincidences were real coincidences he moved the top counter out of the geometrical beam and found that the number of coincidences dropped to the calculated accidental coincidences. This result was believed to prove that the coincidences were caused by single ionising particles that passed in a straight line through the lead. From the fact that these particles were absorbed at about the same rate as the penetrating part of the cosmic radiation Rossi concluded that this part of the radiation consisted of high energy

charged particles.

Since this conclusion is rather at variance with preconceived notions of the character and properties of such high energy radiation, it is of interest to see whether any alternative explanations of this result are tenable.

In Rossi's experiment the stack of lead between the counters had a cross section about equal to that of the counters. Around each counter there was a lead shield several centimeters thick. Under these conditions it is clear that the coincidences could be caused by the passage of some radiation outside the lead stack. This radiation could produce secondaries in each lead shield and these secondaries could operate the counters to register a coincidence. If this process actually occurred then the number of coincidences observed would depend upon the cross section of the lead between the counters. To test this point three counters were set up with 66 cms. of lead between. The cross section of this lead could be made either 5x20 cms. or 20x20 cms. Readings were taken over 24 hour periods with the lead column alternately of these two cross sections. Over a total time of 256 hours no difference between the counting rates could be observed. This result means that the coincidences are caused by something that passes through the lead between the counters, and furthermore, this radiation must pass almost in a straight line through the lead.

The next question that arises is the following: are all of the coincidences caused by the passage of the same particle through the three counters? Secondary particles could cause coincidences in two ways. The secondaries may be released immediately above the counters and follow in the line of the primary through the counters, or the secondaries may make an appreciable angle with the path of the primary so that primaries that do not pass through the counters may still give rise to coincidences. A number of experiments have been performed that throw light on this last process.

To a first approximation the experimental result that the number of coincidences is independent of the cross section of the lead between the counters shows that secondaries play a minor role. The following experiments enable an estimate of their importance to be made.

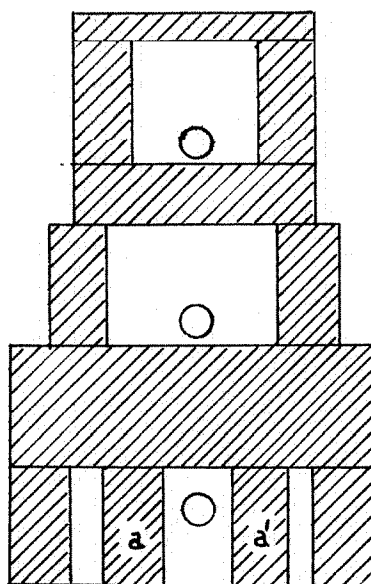


Fig. 6

Three counters were arranged as shown in Figure 6. The lead between the counters totalled 15 cms. and above the top counter was a lead plate 2.5 cms. thick. The number of coincidences per hour was obtained with the lead a-a' in the position shown. These two lead blocks were then removed and the rate measured again.

Removing the lead blocks decreased the rate about 7%. It is easy to see that the extra coincidences caused by the lead blocks must arise either from a bending of a particle which has passed through the other two counters or from a secondary particle generated in the extra lead. From the geometry of the arrangement it follows that a deflection of a primary particle would have to be through a large angle and hence this process must be excluded as rare. This means that most of the extra coincidences are due to secondaries released in the extra lead and making a large angle with the path of the primary. There is no way of telling whether the primary has passed through the first two counters or whether secondaries are released beside each counter to operate it. In any case one must conclude that such large angle secondaries are not the principal cause of the coincidences.

The next experiment was performed with the same arrangement as Figure 6 but with the extra lead blocks removed. The counting rate was measured with and without the 2.5 cm. lead plate above the top counter. It was found that the lead plate above the top counter increased the counting rate about 5.5%.

In terms of secondaries this result means that secondaries produced in the lead above the top counter operate the top counter while the primary goes on through the other counters or releases secondaries near these counters which operate them.

It is clear that secondaries can be formed before the primary is near the end of its range, or else that the secondaries have sufficient energy to penetrate 15 cms. of lead. Later it will be shown that this is not very probable, and so these two experiments show conclusively that coincidences can be caused by secondaries released at intervals along the course of the primary, and making an appreciable angle with the direction of the primary. Again it must be stressed that coincidences caused in this way are comparatively infrequent.

It might be asked why these experiments show the presence of secondaries while the first experiment did not. Probably the answer is that in the first experiment there was always 5 cms. of lead above the counters and this was sufficient to absorb the secondaries that were produced.

The most direct way of measuring the effect of secondaries upon the coincidence rate is to move one of the counters just outside the geometrical beam defined by the other counters. This experiment was attempted by the writer but instrumental difficulties prevented its successful conclusion. Since that time Rossi⁽⁸⁾ has published an account of a similar experiment. He set up three counters separated by 90 cms. of lead. The middle counter could be moved laterally 3 cms., just enough to put it

out of the geometrical beam. He found that moving this counter changed the counting rate from 1.92 per hour to 0.29 per hour. The accidental coincidences per hour were about 0.01 and so could be neglected. This result means that about 15% of the coincidences between counters separated by 90 cms. of lead are due to secondaries making an appreciable angle with the path of the primary radiation. Alternately one could say with Rossi that the 15% are due to a slight deflection of the primary particle but it is believed that the experiments of Figure 6 show definitely that secondary particles are present and there is no reason to doubt that these secondaries are just as significant in this experiment.

Another experiment by the writer shows that the secondary particles whose presence is proven above, are not able to penetrate more than two or three centimeters of lead. For this experiment the counters were arranged as shown in Figure 7, with 36 cms. of lead between the counters and a 2.5 cm. lead plate above the topmost counter. It will be noted that the difference between the two parts to this experiment lies in the arrangement of the lead around the bottom counter. In part (a) the lead plate above the top counter increased the counting rate 9% with a probable error of about 2%. In part (b) no increase could be observed within the limits of error, about 5%. This experiment is interpreted as follows.

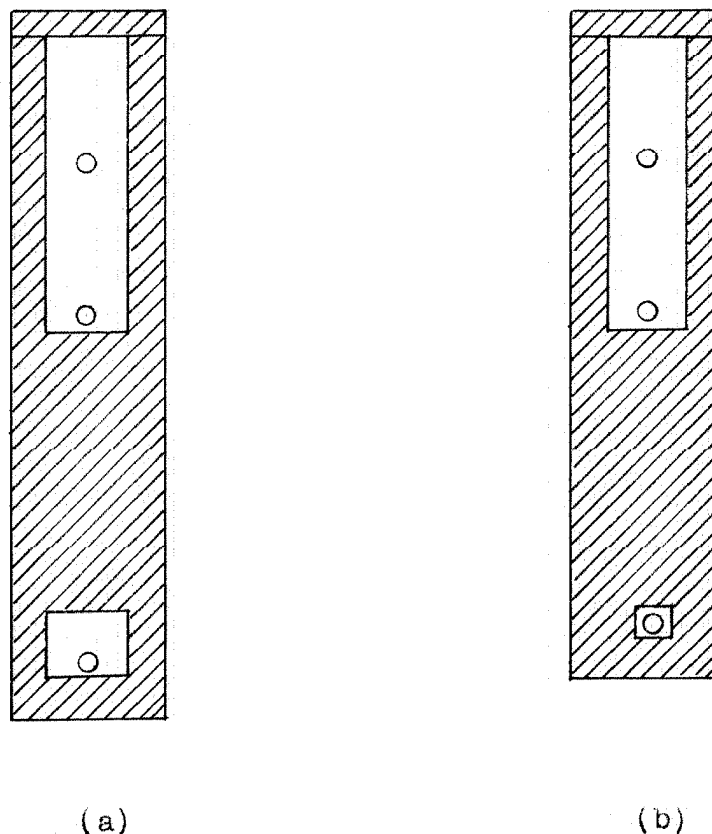


Fig. 7

In part (a) secondaries generated in the top lead plate operate the two top counters while the primary continues through, or more probably near, the bottom counter. Occasionally the primary generates a secondary in the lead a small distance above the bottom counter and this secondary passes through the bottom counter and registers a coincidence. In part (b) secondaries generated near this counter by a primary passing at some distance from it are not able to reach it because of the lead that closely surrounds it. Hence the effect of the lead plate above the top counter must be greatly reduced.

It would be expected that if the experimental results were more accurate it would be found that in part (b) the lead plate

would still have a slight effect on the counting rate.

From this experiment one cannot say what the range of the secondary actually is, but it is possible to say that these secondary particles that make a large angle with the direction of the primary have a very small range as compared with the primary radiation.

All of the above discussion refers to secondaries that make an appreciable angle with the path of the primary. If the primary is itself an ionising particle there is no way of telling the presence of secondaries that follow in nearly the same path as the primary because these can produce no new coincidences. On the other hand, if the primary is unionising then some primaries may pass through the top counter without being accompanied by an ionising secondary. Such primaries will not register coincidences. If now some heavy material is placed immediately above the top counter, the probability that the primary will be accompanied by an ionising secondary when it passes through the top counter is greatly increased. For this reason the presence of lead above the top counter should lead to an increase in the counting rate. To separate this effect from the increase due to secondaries making an appreciable angle with the primary, it is only necessary to make the lead plate the same size as the geometrical beam. This has been done in the following experiment.

The three counters were arranged in a vertical line with 20 cms. of lead between. A lead bar 2.5 cms. wide and 3.0 cms.

thick could be placed immediately above the top counter. If this lead introduced secondaries in the path of an unionising primary then, as stated above, it would cause an increase in the counting rate. The results obtained were:

Without the lead above the top counter --- 4878 counts in
161.8 hours = 30.1 ± 0.43

With the lead above the top counter ----- 4886 counts in
158.5 hours = 30.9 ± 0.44

Thus the effect, if any, is quite small.

This result means that the radiation that can penetrate 20 cms. of lead is either an ionising radiation or that the primary unionising radiation is always accompanied by an ionising secondary. Because of the presence of the air and a considerable thickness of concrete in the roof of the building this last statement is not unreasonable.

There is thus no direct evidence as to the nature of the primary penetrating radiation. However, it can be asserted that this radiation for the most part penetrates lead without appreciable deviation. Occasionally it gives rise to secondaries that deviate widely from the primary direction. If the primary is unionising then at sea level it is always accompanied by a secondary which will operate a counter that the primary passes through. The simpler hypothesis, that the primary is a very penetrating particle, is consistent with all the Geiger counter experiments.

VIII. EXPERIMENTS IN THE SHOWER PHENOMENA

By the term "cosmic ray shower" is meant the simultaneous occurrence of a group of particles diverging from a small region. Although the showers were first discovered by Geiger counter experiments, some of their general characteristics are best shown by photographs taken with the counter controlled cloud chamber. Typical showers photographed with the Anderson cloud chamber are shown in the following pictures. The left hand section is the direct view, the other is a mirror image taken for stereoscopic purposes. Particles showing a counter clockwise rotation in the direct view have a positive charge.

In all the pictures except the first there is a lead plate across the chamber. The chamber is controlled by the coincidences between two Geiger counters placed immediately above and below the chamber. In most cases there is also a lead bar about an inch thick just above the top counter. There is no doubt that the expansions take place as soon after the passage of the particles as could be desired. This is so because the pictures taken with the counter control compare favorably with the best of those taken by the random method for sharpness of the tracks.

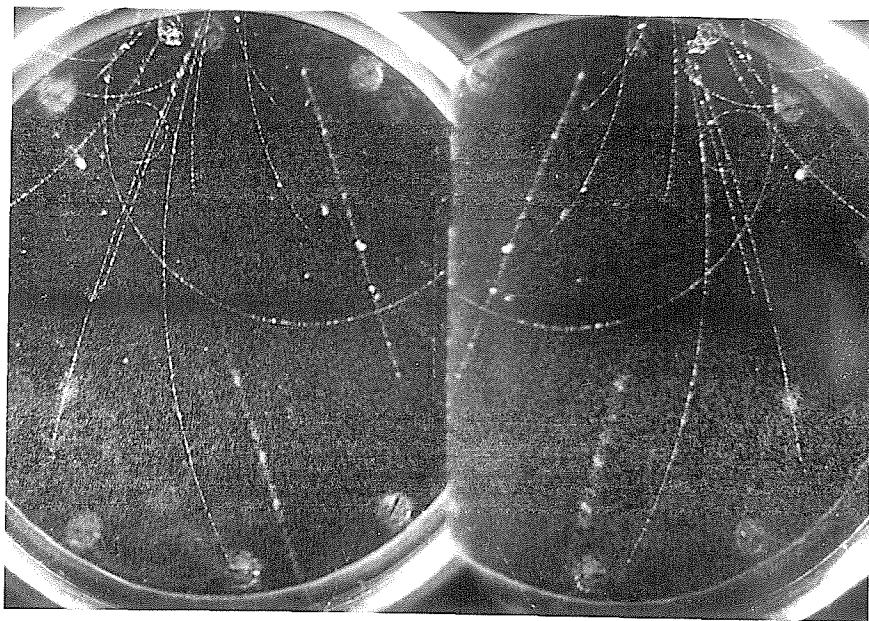


Fig. 8

A typical small shower. The two high energy particles occurred earlier. Note the low energy particles presumably arising from photons absorbed in the walls or gas of the chamber. If the field had not been present it is evident that the shower particles would have remained in a fairly close bundle.

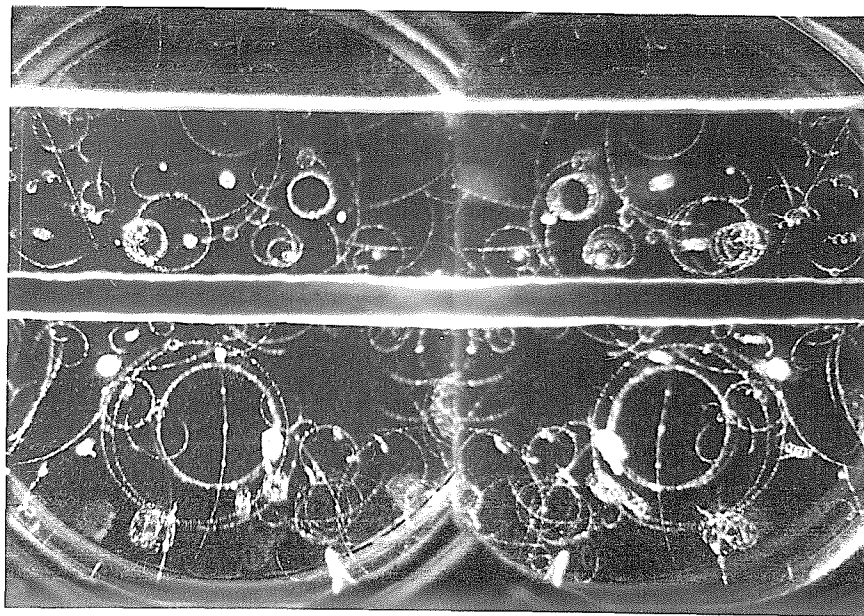


Fig. 9

A group of over 80 particles travelling almost at right angles to the plane of the chamber. Obviously these must arise from a number of different centers. There are a few particles making a much smaller angle with the plane of the chamber and hence the shower must consist of particles diverging widely as well as arising from a number of centers. The energies of the particles range up to 10 million e-volts.

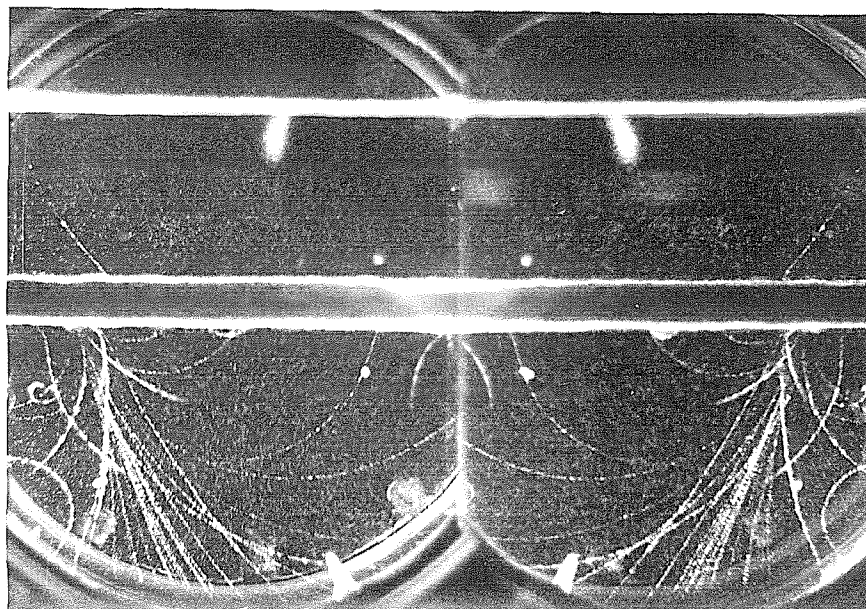


Fig. 10

A shower arising from the absorption of a high energy photon in the lead bar. The shower particles have a much higher energy than in the average shower. The total energy is about 2.5×10^9 electron volts. There are a few particles arising from the absorption of the low energy photons that always seem to accompany the showers. A close inspection of this photograph shows that the particles actually diverge from two centers in the lead. It is difficult to see what operates the top counter unless it is the particle that starts upward from the lead.

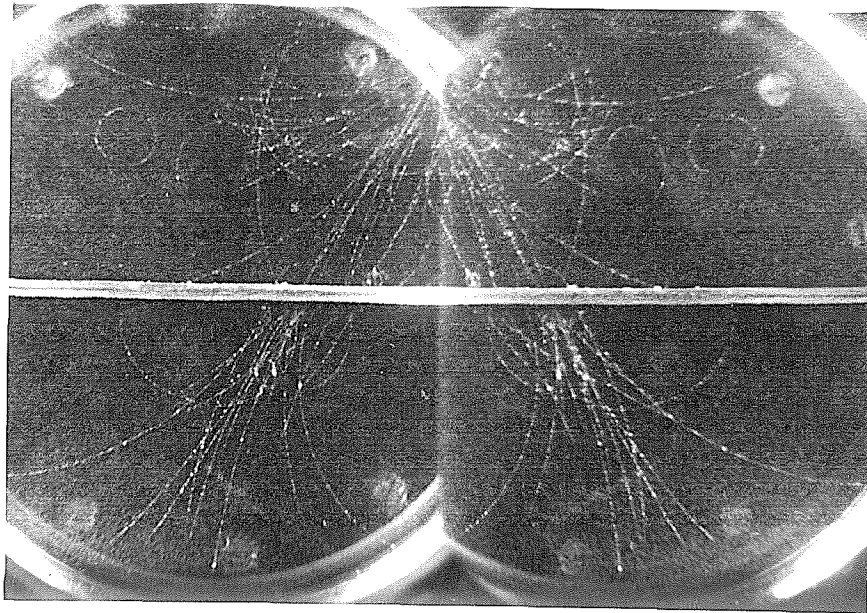


Fig. 11

An example of associated showers. Clearly more particles emerge from the lead bar than enter it. This new shower produced by the absorption of photons in the lead maintains the direction of the original shower.

A study of these and other photographs taken with the Anderson cloud chamber leads to the following conclusions regarding the showers.

- 1 About 88% of the track pictures show single tracks which pass through the 1 cm. lead plate in most cases without deflection or production of secondary particles.
- 2 In a general way, the greater the number of tracks in a shower the more rare the event.
- 3 Even though showers are relatively rare, it is clear that they are responsible for a much larger percentage of the total ionisation than their number would indicate.
- 4 Showers are caused by the absorption of photons. Even the production of a pair by an electron passing through the lead is a very rare event.
- 5 When the origin of a shower is photographed, it is apparent that but for the magnetic field the particles would usually be quite closely collimated.
- 6 A shower is nearly always accompanied by a spray of soft secondary photons.
- 7 The particles ejected from the main shower center will have energies of the order of 10^8 electron volts. Particles arising from the absorption of the secondary photons will have energies of the order of 10^6 electron volts.
- 8 The total energy as well as the number of particles in the showers, varies between wide limits. There is no obvious relation between energy and number of particles.

9 When one shower occurs there is a good chance of another occurring in its immediate vicinity provided some heavy matter is present. In other words the shower photons appear to come in groups. Sometimes, as in Figure 10, these photons will be absorbed within a very short distance of each other and thus give rise to showers diverging from almost coincident centers.

10 The secondary shower photons are widely distributed in direction.

These facts, deduced from the photographs, will give a better understanding of the experiments to be described below.

The first type of shower experiment consists in arranging three counters below a plate of heavy material in such a way that at least two, and preferably three particles from any event in the material are needed for a coincidence to be registered. The rate of coincidences as a function of the thickness of material is then found. The curve thus obtained will be called a "shower curve". Typical curves by Rossi,⁽⁴⁾ Funfer⁽⁹⁾ and the writer are shown in Figure 12. In Rossi's experiment only two particles were needed to register a coincidence. In Funfer's experiment three particles were needed for all except the showers arising in a limited region of his lead, and in my case three particles were needed for all the coincidences. It is interesting to note that in spite of these different conditions, the curves obtained differ essentially only in the magnitude of the effects. Experimental arrangements will be described later that give quite different shower curves.

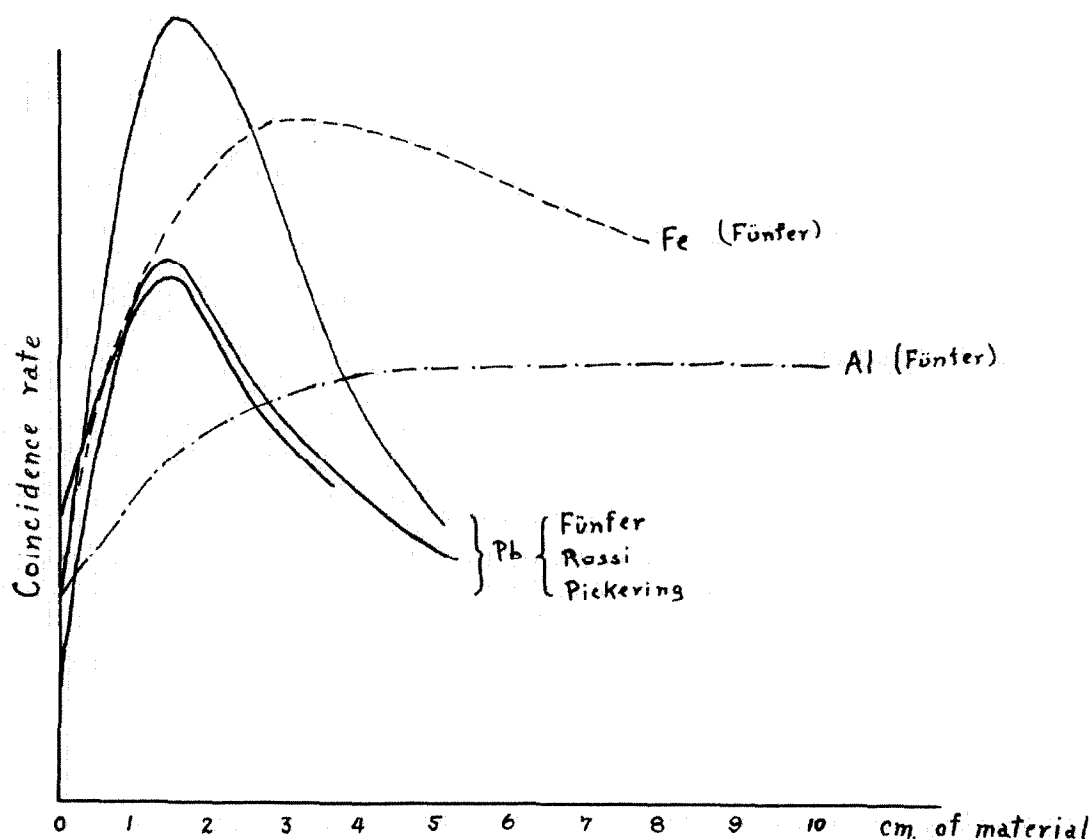


Fig. 12

From the shape of these curves one can draw certain conclusions concerning the production of showers.

- 1 More showers are observed under lead than under any other material tried.
- 2 The thickness of material for a maximum number of showers is a minimum with lead whether expressed in centimeters or in grams per square centimeter.
- 3 The absorption of the shower producing radiation in lead is far more rapid than that of the general cosmic radiation.

An analysis of these shower curves can be made using the following postulates.

- 1 The shower producing radiation is unionising.
- 2 The shower producing radiation loses its energy in sudden large amounts and is absorbed approximately according to an exponential law.
- 3 When a shower occurs electrons go out in the forward direction and a photon radiation spreads in all directions. One of these photons can be absorbed in a counter and register an impulse.
- 4 The shower particles will be assumed to be absorbed according to an exponential law. Even if these particles have a range the fact that they are widely distributed in energy should lead to a type of absorption that will approximate an exponential absorption.
- 5 The secondary photon radiation is absorbed more rapidly than the shower electrons.
- 6 The shower producing radiation is itself produced from some primary more penetrating radiation.

Three types of shower experiment will be discussed. Only simple one dimensional cases will be treated, that is, the beam of radiation will be taken as vertical and differences in path length to the various counters will be neglected. The data do not warrant any more elaborate treatment.

The first case is that of three counters beneath a plate of heavy material, (Figure 13).

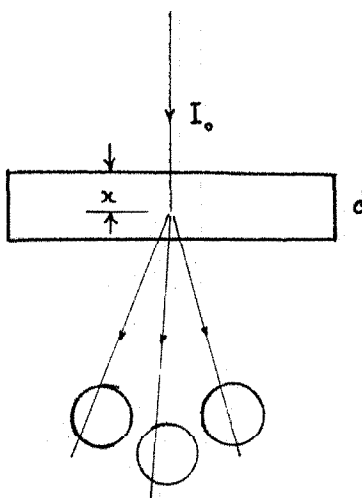


Fig. 13

Let the shower producing radiation have an intensity I_0 at the upper surface.

Let this radiation be reproduced from a radiation of intensity J , where J will be assumed constant throughout the material, and let the rate of reproduction be α per cm. of material.

Then, in a thickness dx ,

$$dI = (-\mu I + \alpha J) \cdot dx$$

where μ is the absorption coefficient of the shower producing radiation.

On integrating,

$$I = I_0 e^{-\mu x} + \frac{\alpha}{\mu} J (1 - e^{-\mu x})$$

The number of showers formed in dx is,

$$dN_s = \mu I \cdot dx$$

Let the absorption coefficients of the shower electrons and secondary photons be u and v respectively.

If there are sufficient electrons and photons leaving the shower center in the direction of the counters, then the probability of a coincidence being recorded from a shower that

starts a distance x from the top of a sheet of material of thickness d , is given by $e^{-\mu(d-x)} + e^{-\nu(d-x)} - e^{-(\mu+\nu)(d-x)}$. This expression may be simplified by substituting $e^{-w(d-x)}$, where w is an effective absorption coefficient. Clearly w will depend on the geometrical arrangement of the counters and if the counters are widely separated it will approach ν because it has been seen that the shower particles are in a fairly narrow beam and hence cannot operate more than one counter under these conditions. Coincidences then must be caused by shower photons operating at least two of the counters. In the rest of this analysis w will be used.

The number of coincidences arising from showers generated in the element dx is given by:

$$dN = e^{-w(d-x)} \mu I_0 dx$$

Substituting for I and integrating between the limits zero and d , one obtains the total number of coincidences caused by the presence of the material above the counters;

$$N = \frac{\mu I_0 - \alpha J}{w - \mu} (e^{-\mu d} - e^{-w d}) + \frac{\alpha J}{w} (1 - e^{-w d})$$

To investigate this expression we first find the maximum by equating the derivative to zero. This gives:

$$d_m(w - \mu) = \log_e \left(\frac{w}{\mu} - \frac{\alpha J}{\mu I_0} \right)$$

We next note that for large values of d , $N \sim \alpha J/w$ approaches the exponential $e^{-\mu d}$ provided w is larger than μ . Hence from an examination of the curve beyond the maximum we can find μ .

For very large d , the number of coincidences becomes $\propto J/w$, provided that J can be considered constant throughout the material. However, this will still be true if the absorption coefficient of J is small compared with that of I . Physically this is to be expected so that under large thicknesses of material the number of coincidences should be proportional to J .

Before discussing the experimental results in the light of the above function for N , it will be worthwhile to consider some further results of the theory.

The next case is that of three counters above a sheet of material, (Figure 14).

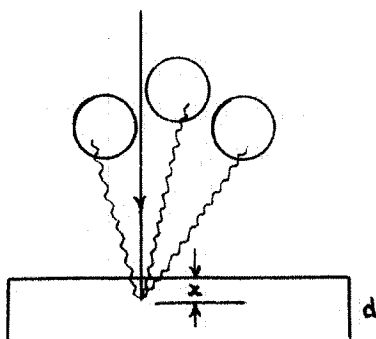


Fig. 14

As before a one dimensional problem will be assumed with the shower producing radiation coming vertically downwards. The only way in which a coincidence can be recorded is by the secondary shower photons being absorbed in the three counters. The possibility of shower particles being deflected 180° in sufficient numbers to cause a coincidence will be neglected. Using the same notation, we then have for the contribution of the element dx :

$$dN = e^{-\mu x} \mu I \cdot dx$$

In this case it is probably safe to neglect the contribution of J so that: $I = I_0 e^{-\mu x}$

Integrating through a thickness d, the total number of coincidences is given by:

$$N = \frac{\mu I_0}{\nu + \mu} (1 - e^{-(\nu + \mu)d})$$

As would be anticipated, the number of coincidences increases exponentially to a maximum. Experimentally this is found to be the case.

An experiment due to Sawyer⁽¹⁰⁾ will now be considered. This time one counter is above the lead and two below, (Fig. 15). If the primary shower producing radiation were ionising, then this experiment would not be essentially different from the first case except for the magnitude of the effect. Actually there is a great difference, and the result can be predicted by the theory.

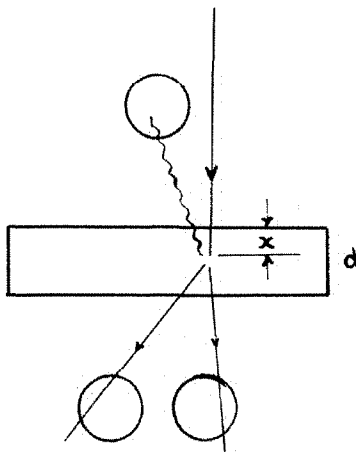


Fig. 15

The reproduction of showers from the radiation J will be neglected, so that the number of showers formed in the

element dx is given by : $\mu I_0 e^{-\mu x}$. The probability of a coincidence is given by : $e^{-vx} e^{-w(d-x)}$, and hence :

$$dN = e^{-wd} e^{-(v-w)x} \mu I_0 e^{-\mu x} dx$$

Integrating up to a thickness d as usual, one obtains :

$$N = \frac{\mu I_0}{w-v-\mu} (e^{-(v+\mu)d} - e^{-wd})$$

This function has a maximum given by :

$$d_m(w-v-\mu) = \log_e \frac{w}{v+\mu}$$

and for large d it approaches the exponential $e^{-(v+\mu)d}$.

These expressions cover the main types of shower experiment. In spite of the many simplifications of the theory the functions obtained fit the experimental curves quite well. The following graphs show this.

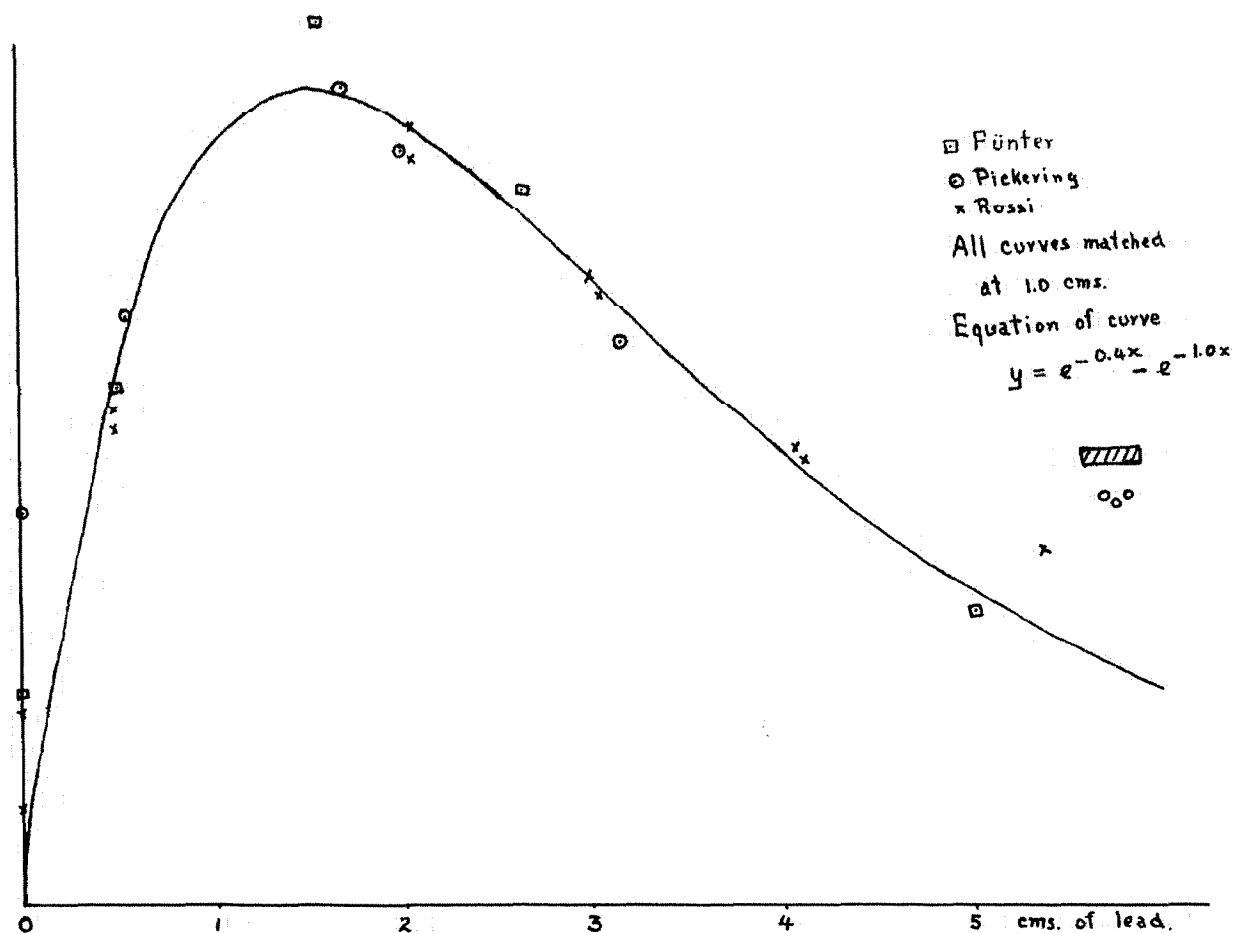
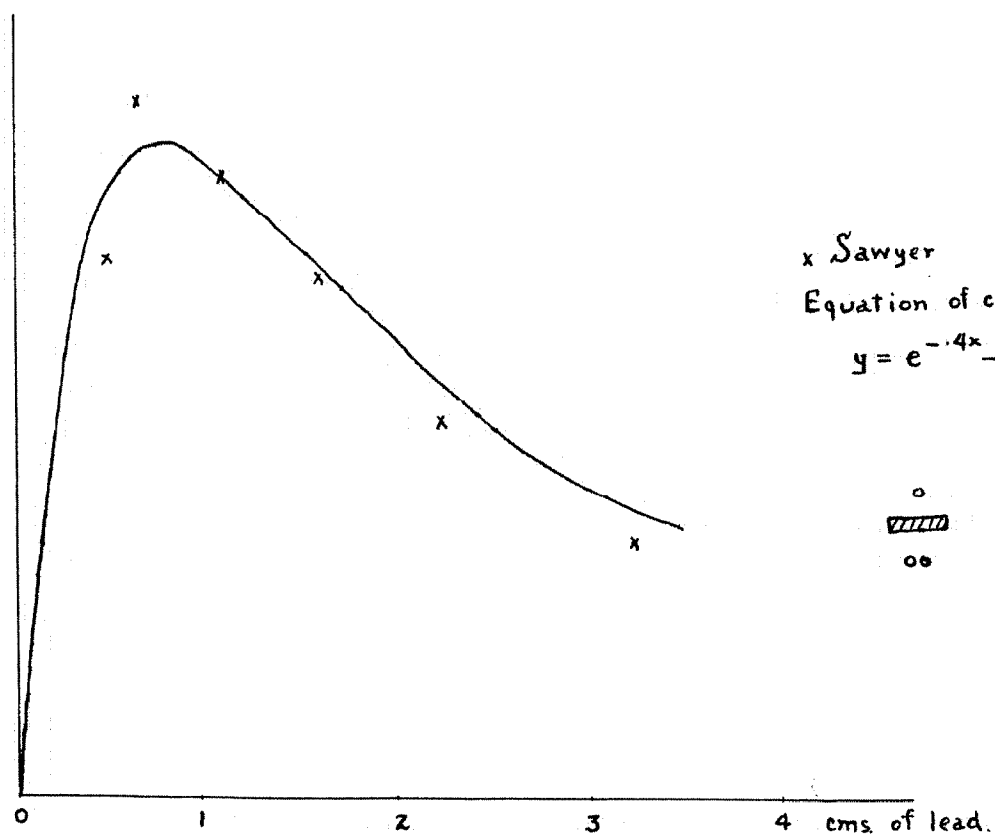
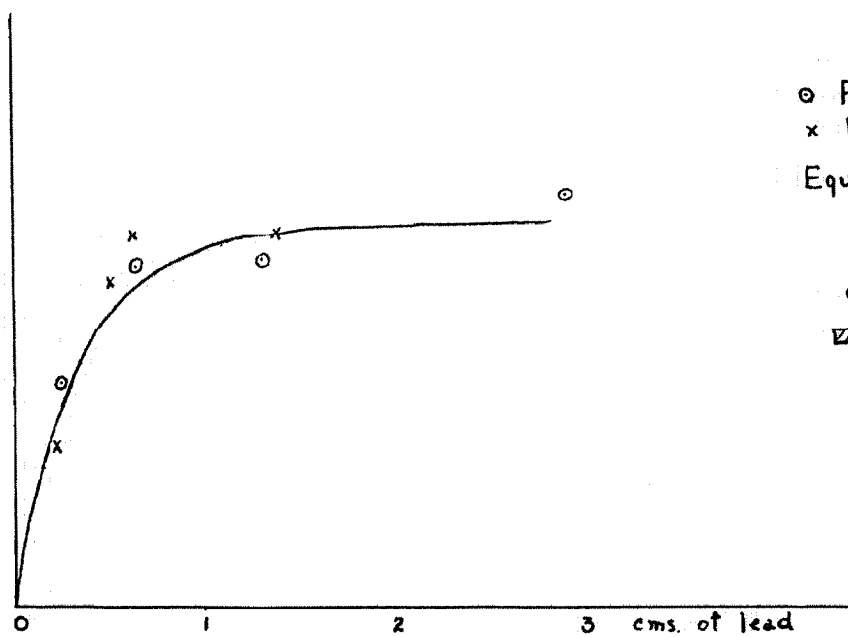


Fig. 16a



Before entering into a discussion of the numerical results to be obtained from the theory, it should be pointed out that the agreement between various observers is not good enough to give more than very approximate values to the various absorption coefficients. The chief reason for this lack of agreement is of course the great complexity of causes that give rise to coincidences. It has already been indicated that lead beside or below the counters can cause coincidences, and furthermore the number of these coincidences increases with the number of showers in the vicinity, so that the arrangement of the matter around the counters must affect the results obtained. Another difference lies in the arrangement of the counters themselves. As shown in the above theory the slope of the experimental curve, which depends on the effective absorption coefficient w , must be changed for different counter arrangements because of the dependence of w on the counter geometry. This is borne out by experiments to be discussed later.

As far as the mathematical theory is concerned, the expressions obtained are symmetrical in μ and w . Hence the shape of the curves will be the same whether the shower producing radiation or the shower particles have the larger absorption coefficient. A priori one would expect that the shower particles would be more readily absorbed, however, a more consistent set of coefficients for the three experiments can be obtained if one says that the shower producing radiation has the largest absorption coefficient. This has been done for the above curves.

Values obtained for the coefficients are as follows :

Lead. Absorption coefficient of the shower producing

radiation ----- 1.0 per cm.

Apparent absorption coefficient of the shower

particles ----- 0.4 per cm.

Absorption coefficient of the shower

photons ----- 2.0 per cm.

Iron. Absorption coefficient of the shower producing

radiation ----- 0.8 per cm.

Apparent absorption coefficient of the shower

particles ----- 0.1 per cm.

Aluminum. Absorption coefficient of the shower producing

radiation ----- 0.4 per cm.

Apparent absorption coefficient of the shower

particles ----- 0.02 per cm.

An inspection of these figures reveals two facts.

(a) The shower producing radiation is absorbed nearly according to a mass absorption law.

(b) The shower particles are absorbed nearly according to a Z squared law.

Assuming that the experimental results are good enough, then these results will have some validity provided that particles from showers arising in different materials have the same average energy or at least the same absorption coefficient in a given material.

If these figures are extrapolated to values for air one obtains for the absorption coefficient of the shower producing radiation about 15 per meter of water and for the shower particles about 0.5 per meter of water. If this extrapolation were valid it would imply that charged particles having energies about equal to those of the shower particles would be absorbed by the air at the rate given above. It is interesting to compare this deduction with the observed fact that the field sensitive part of the radiation is very soft, having an apparent absorption coefficient of perhaps 1 per meter of water.

Again, consider the effect of taking three counters arranged to record showers but with no extra material above the counters, up to the top of the atmosphere. Most of the way up the curve would approximate an exponential absorption with coefficient about 0.5 per meter of water. This would gradually turn over into a maximum about 0.25 meters pressure below the top of the atmosphere and then rapidly descend to zero. As yet there is no data for this curve but a few experiments have been performed showing the number of showers that emerge from a lead plate at various altitudes. These seem to point to an absorption coefficient of about 0.5 per meter of water. This has been assumed to be the rate of absorption of the shower producing radiation itself.

In order to understand further the mechanism of shower production, some new experiments have recently been completed, and will now be discussed.

The first question that arises concerns the shower phenomena under thick plates of material. The analysis of the curves gives good agreement up to about 5 cms. of lead, but for greater thicknesses the theory predicts fewer coincidences than are actually found if the factor in J is neglected. With 15 cms. of lead above three counters I found that the counting rate was almost twice that with no lead. To verify that this was not due to showers entering the counters at a large angle with the vertical, lead was put all around the counters and the rate remained about the same. Hence there is no doubt that showers do emerge from lead plates of this thickness. To interpret this result one must say either : the shower radiation can be reproduced from some primary radiation that is much less absorbable, or : the shower radiation consists of two parts that vary greatly in their absorbability. Consider the latter possibility first. The cloud chamber pictures show shower producing photons of a wide range of energies and yet the maximum of the shower curve is very pronounced. This would indicate that shower producing photons of all energies have the same absorption coefficient in the lead and hence that this second possibility is not very probable. Another more cogent reason for accepting the first postulate is the theoretical result that particles of high energy should

lose energy in sudden large jumps. At each jump a photon is released and this of course can be absorbed with the production of a shower. Another evidence for the production of showers from a penetrating radiation is the appearance of showers under large thicknesses of water.

To learn something further of the shower production under large amounts of matter the following experiment was devised. The counters were arranged as in Figure 17a the top lead plate being 1.7 cms thick and the other lead variable.

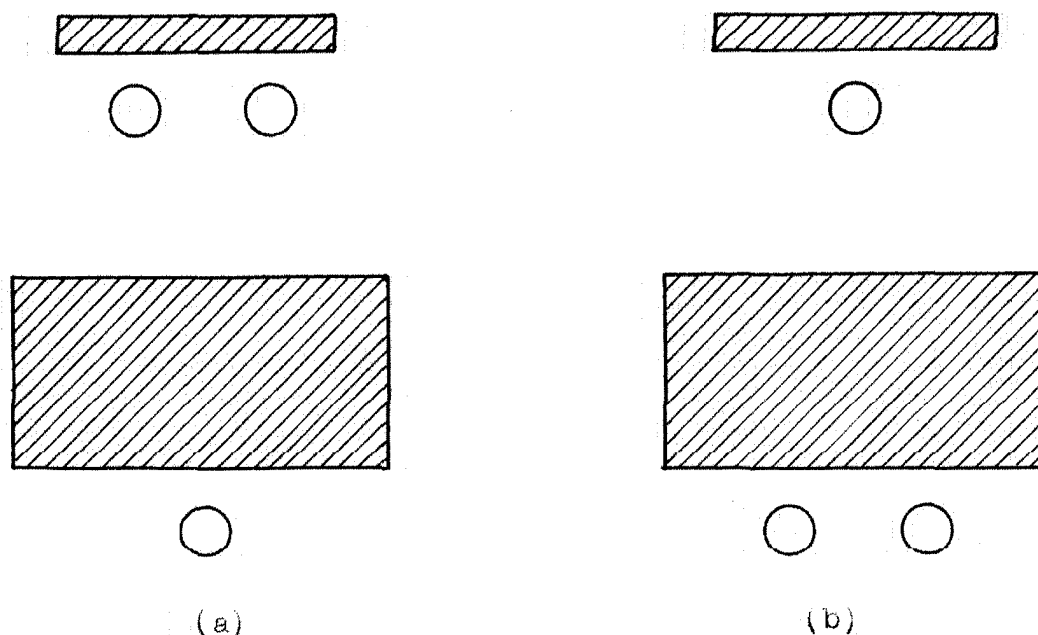


Fig. 17

It was found that with no lead between, the top lead plate caused an increase of 5.8 counts per hour. With 5 cms. between this had dropped to 0.6 per hour and with 10 cms. between the change was about 0.3 per hour. This result shows that particles from showers generated in the top lead have a penetrating

power less than 5 cms. of lead. This could have been anticipated from the cloud chamber measurements which show that most of the shower particles have energies under 100 million electron volts. The small remaining effect under 10 cms. of lead may be due to the few showers in which the particles have a greater energy or to single particles which generate a secondary in the topmost lead and then go on through the lead to operate the bottom counter. There is also the possibility of associated showers occurring in the top lead and then again near the bottom counter. The data show that even with 5 cms. of lead this process is quite rare. It is believed that this result offers good evidence for the suggestion made above that the associated showers are caused by groups of shower producing photons and not by single photons suffering successive catastrophes.

The counters were now arranged as shown in Figure 17b. With 10 cms. of lead between and no lead above the rate was about 0.5 per hour faster than with the same lead but arrangement 17a. The lead above increased the count another 0.5 per hour. With the three counters side by side below the 10 cms. of lead the rate was 10.7 per hour, nearly as fast as with the arrangement 17a with no lead between and 1.7 cms. above. The chance coincidences occurred about 2.0 times per hour.

These results are interpreted as follows. Assuming that the shower producing radiation can be reproduced from an ionising radiation that is very penetrating, then the arrangement of 17b will be sensitive to such "secondary" shower radiation,

while that of 17a will not unless two secondary showers are produced. The incoming particle will operate the top counter and then generate a shower producing photon in the lead. This photon will be absorbed almost immediately and the resulting shower will be detected by the two bottom counters. The fact that 17b shows a slightly greater rate than 17a is believed to be evidence that such a process actually occurs. The addition of the lead above the top counter causes another increase because, as shown above, the incoming particle can generate a secondary particle in this lead which can operate the top counter. With the three counters below the lead the rate is about 8 times what it is with one counter above the lead. At first sight this might seem to be too large a change for the above hypothesis, however it must be remembered that in this last case particles falling anywhere on the surface of the lead block could give rise to a shower photon that would cause a coincidence, while in the first case only those particles that actually pass through the top counter can be effective. The upper surface of the lead was about 8 times that of the counter so that the magnitude of the change is about right.

To sum up, these experiments show :

- (a) The shower particles have a penetrating power on the average of less than 5 cms. of lead.
- (b) The associated showers are caused by groups of shower producing photons rather than single photons that give rise to a series of showers.

(c) The showers under large thicknesses of lead are caused by photons that are produced in the lead by an incoming ionising radiation.

The next question concerns the mechanism of shower coincidences when the counters are so widely separated that the particles must be on widely divergent paths. A shower curve was found when the counters were as shown in Figure 18. The result is also shown in Figure 18. It will be noted that the maximum counting rate occurs when there is about 1.0 cms. of lead above the counters instead of the usual 1.6 cms.

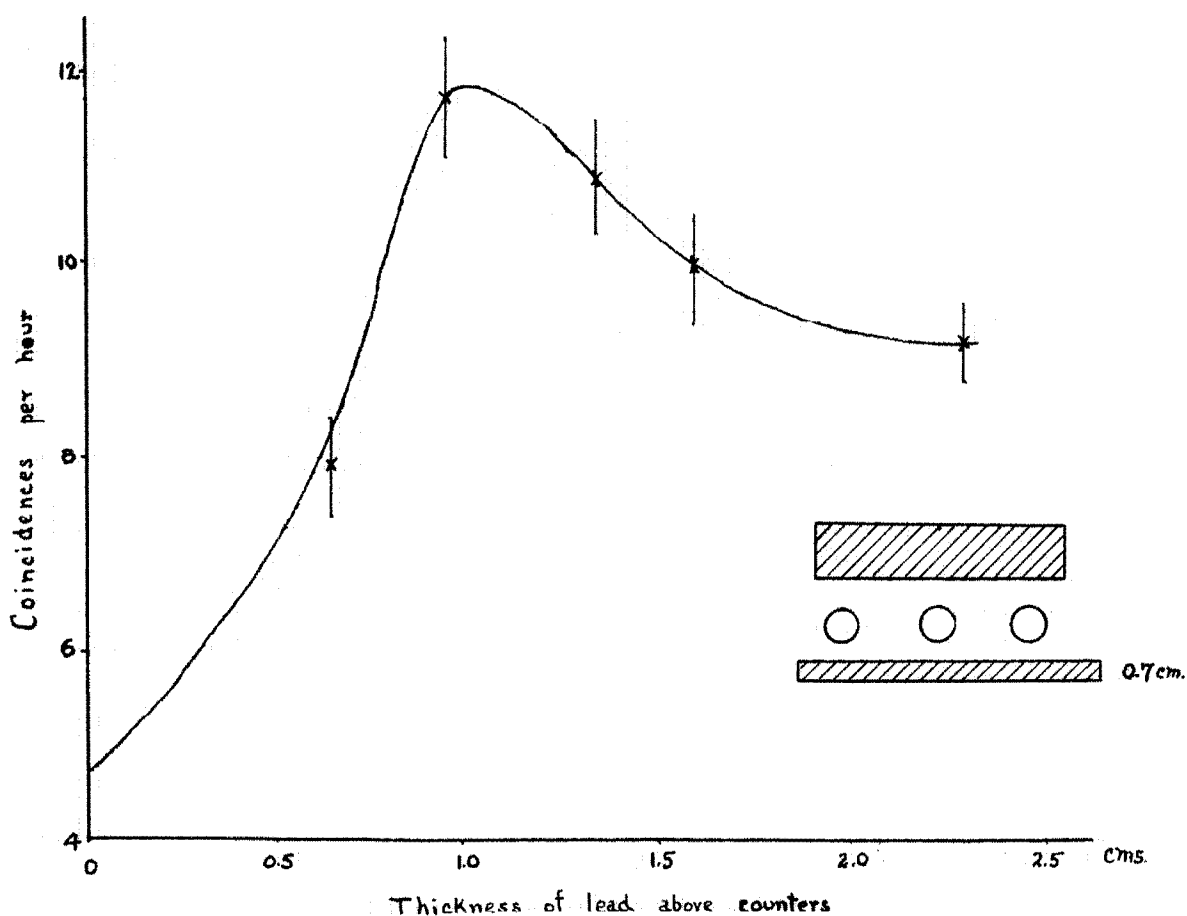


Fig. 18

There are two factors responsible for this change in the shape of the curve. First, radiation travelling from the shower center to the counters will travel through much larger thicknesses of lead, and second, at least two of the counters must be operated by the shower photons rather than the shower particles. Both these effects will change the curve in the observed direction. If it be assumed that the coincidences are indeed caused by the shower photons then the thickness of lead for the maximum number of coincidences can be calculated using the data of the other shower curves. This turns out to be at 0.8 cms. The agreement with the observed value must be regarded as fortuitous because the approximations made in the theory cannot hold in this case.

A little data has been obtained on what might be called the transition effect for showers. The counters were arranged as in Figure 18 and curves taken under three sets of conditions as follows. First, the curve of Figure 18 with the counters under a thin wooden covering out on the roof, second with the counters in a room on the top floor of Bridge laboratory with perhaps 20 cms. of concrete above, and lastly in the same room but with an additional iron plate 1.9 cms. thick immediately above the lead. All these curves are collected in Figure 19. The effect of a lead plate 0.7 cms. thick immediately below the lead is also shown, and for comparison the curve obtained with the counters closer together. This last curve was taken in the room on the top floor, and it should be noted

that the ordinates are divided by two.

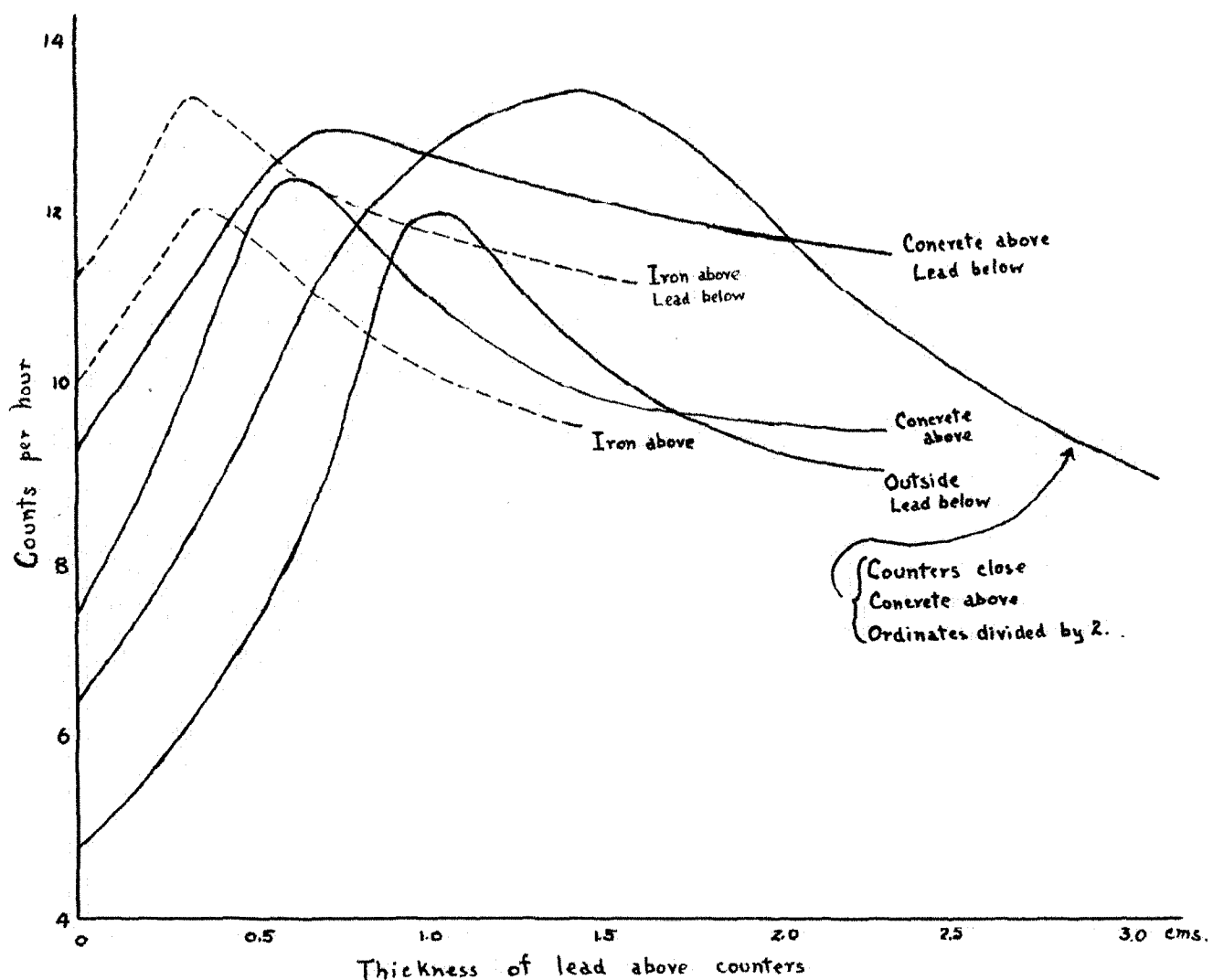


Fig. 19

An inspection of these curves shows the following :

- (a) The showers are about twice as numerous with the counters close together instead of widely separated.
- (b) At least with the counters widely separated the maximum of the shower curve occurs at smaller thicknesses of lead when additional matter is above the top lead.
- (c) The maximum number of showers observed does not change

greatly when additional matter is above the lead.

(d) Lead beneath the counters increases the count but does not greatly change the shape of the curves.

Consider these points in the above order:

(a) Coincidences are more numerous when the counters are close together because in this case shower particles can pass through them and register a coincidence. When the counters are widely separated at least two of them must be operated by a shower photon. Even if these photons are quite numerous the probability of a coincidence is still low because of the small probability that a photon will be absorbed in the counter.

(b) When additional matter is placed immediately above the lead the atoms of this matter absorb the radiation just as the lead atoms, (after correcting for the different atomic number) and so the additional matter has the same effect as additional lead. When the coincidence rate is plotted against the thickness of the lead plate then the curve merely starts at a different point when additional matter is above the lead. Comparing the two curves we see that the 1.9 cms. of iron is equivalent to about 0.3 cm. of lead. Assuming a Z^2 law of absorption this iron would be equivalent to about 0.84 cm. of lead. As this is more than twice the observed equivalent thickness other factors must be complicating the picture. These factors are the possibility that the shower particles from the iron have a different energy and absorption in the lead than the particles from showers in the lead, and the reproduction of the radiation from some primary.

(c) The fact that the maximum number of showers remains nearly constant implies that when small thicknesses of matter are above the counters the reproduction of the radiation from some primary radiation is not of great importance. Each incoming shower producing photon has a certain chance of causing a coincidence and this chance depends only upon the total amount of matter above the counters. If most of the shower producing radiation that struck the lead had originated in the iron above the lead, then the shower curve with the iron present would have the same shape as before except that the ordinates would be multiplied by some constant.

(d) Lead beneath the counters increases the count first by absorbing shower producing rays that get through the upper lead plate and hence causing coincidences by the shower photons released in these showers, and second by absorbing shower particles from showers in the upper plate and thus producing a gamma radiation that can operate the counters. It should be noted that this gamma radiation is probably the same as the so-called shower photon radiation above. Many of the shower particles will be absorbed in the immediate vicinity of the shower center and hence it is reasonable to suppose that all of the shower photons arise from absorption or annihilation of the shower particles.

Another consequence of these experiments which has not yet been mentioned is that they show very clearly that the shower phenomena as measured with three Geiger counters beneath

a plate of material will depend on the geometrical arrangement of the counters and also on the proximity of material in the walls and roof of the room in which the experiments are performed. Even the electrical shielding of the counters and the material of the counters themselves may be expected to contribute to the results.

Although no reason for an essentially different result with the counters close together is immediately obvious, the fact that most observers agree on the figure 1.6 cms. for the maximum of the shower curve under lead implies that the curve does not depend on the material above the lead. Without further information however this must not be asserted.

IX. THE ALTITUDE VARIATION OF THE SHOWERS

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A Note on the Production of Cosmic-Ray Showers

The cosmic-ray showers, which are shown so beautifully in the counter controlled cloud chamber,¹ have been investigated by numerous observers. The method in general has consisted in putting three Geiger counters below a thin plate of heavy material. The counters are usually arranged so that three particles emerging simultaneously from the plate are required to register a coincidence. Hence a shower will consist of at least three particles associated in time.

This note concerns an experiment dealing with the variation in the number of showers with depth below the top of the atmosphere. The experiment was performed in a tunnel of the Morris Dam of the City of Pasadena. Readings were taken at points where the solid angle down to 45° from the vertical was filled on all sides with a known depth of water. The coincidences were recorded with a vacuum tube circuit similar to those of Johnson and Rossi. The counters were 14 cm long and 2.5 cm in diameter. They were placed as shown in Fig. 1, beneath a lead plate 2.2 cm thick and 20×20 cm in area.

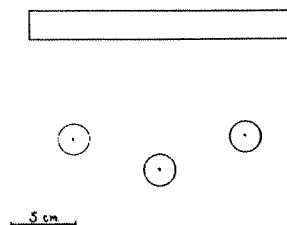


FIG. 1.

Measurements were made of the number of coincidences per hour at three locations as shown in the following table. This table gives the increase in the number of coincidences per hour due to the lead plate above the counters.

(i)	Apparatus on the top floor of Bridge Laboratory	8/hr.
(ii)	Under approx. 4 meters water equivalent below sea level	0.5/hr.
(iii)	Under approx. 10 meters water equivalent below sea level	0.1/hr.

The intensity of the vertical radiation at the three places was measured by putting the counters in a vertical line with about 6 cm between counters (i.e., 12 cm overall). Comparing this with the number of showers emerging from the 2.2 cm lead plate, one obtains,

	Vertical	Showers
(i) At sea level	1.0	1.0
(ii) 4 meters below	0.38	0.06
(iii) 10 meters below	0.20	0.01

A few measurements have been made with varying thicknesses of lead, and these show that the thickness of lead for a maximum number of showers decreases greatly as one goes below sea level.

As a result of these experiments the following conclusions must be reached.

- (i) The sea level radiation responsible for the type of coincidence here involved is softer than the average cosmic radiation.
- (ii) The energy of the shower particles, as measured by the thickness of lead at which the coincidences are of maximum frequency, decreases when the shower producing radiation is filtered through water.

I wish to thank the Water Department of the City of Pasadena for permission to use the Morris Dam.

I also wish to thank C. D. Anderson and R. A. Millikan for many helpful suggestions.

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February 6, 1935.

¹ Anderson, Millikan, Neddermeyer and Pickering, Phys. Rev. 45, 352 (1934).

Recently Rossi⁽¹⁾ has verified this result and other workers have concluded that at high altitudes the showers increase

much more rapidly than the vertical radiation. Most of the data show that the shower producing radiation has an apparent absorption coefficient in air of about 0.5 per meter of water. Some data on the barometer effect on the showers also give about this value. This figure, however, does not have much significance unless the quality of the radiation remains the same at the various altitudes. On this point there is not yet agreement among the various observers. As far as the Morris Dam data are concerned, the evidence is that under the water the maximum of the curve is shifted towards a smaller thickness of lead. In view of the more recent shower transition curves just discussed this result is certainly to be expected with the counters in the arrangement used for those experiments. At the Morris Dam the arrangement of the counters did not differ very greatly from this and so it is reasonable to assume that similar effects would be found. This means that the absorption coefficient for the shower producing radiation must be viewed with caution. However, it can be considered as well established that the shower producing radiation is much softer than the average radiation.

X. THE GEOGRAPHICAL VARIATION OF THE SHOWERS

It has been known for a number of years that the intensity of the cosmic radiation is less in the equatorial band than at other points on the earth's surface. This effect has been explained as due to the earth's magnetic field deflecting incoming charged particles away from the equator. With this in mind it is of interest to know whether the shower producing radiation is affected by the magnetic field of the earth. Cloud chamber photographs show that in most cases the immediate cause of the shower is a photon, but there is a certain amount of evidence that this photon is itself a secondary. If the primary is a charged particle with an energy small enough to be deflected by the earth's magnetic field, then there will be a latitude effect in the number of showers emerging from a given lead plate. If the primary is uncharged, or if the photon itself is the primary, then there will be no change in the number of showers with latitude.

To investigate this point a coincidence recording apparatus was built in a form that could be used on ship board. With this apparatus observations were taken on a voyage from San Francisco to Wellington, New Zealand, and on the return voyage as far as Hawaii.

The coincidence selecting circuit was essentially similar to that used in Pasadena except that some slight modifications were necessary so that the set could be used with both direct

and alternating current. This had to be done because the generators used on ships usually supply only direct current.

The counters used were about 2.5 cms. in diameter and 14 cms. long. They were filled with argon mixed with 20% of air, to a pressure of 5 cms. of mercury. The argon mixture was used because this operates on a lower voltage than air and batteries had to be used to supply the voltage.

Data were taken with the counters in two arrangements. The first was merely with them in a vertical line with about 13 cms. between the top and bottom counters. The frame that held the counters was swung on gimbals to eliminate the effect of the roll of the ship. To measure the showers the arrangement of Figure 20 was used. The lead above the counters was 1.6 cms. thick, that at the sides and below was about 0.6 cms. thick. This extra lead was used to increase the counting rate as much as possible. The daily runs were usually divided with the counters vertical for about 4 hours and in the shower position for about 20 hours. From the ship's log data on the position and barometer were obtained.

The results obtained were not as consistent as was hoped, the probable causes of error being as follows. First, the ship was on a north south course so that the change in latitude was too rapid to allow many counts to be obtained at any given latitude. Second, the voltage delivered by the ship's generators varied greatly. Third, the amount of vibration present varied with the weather and was sometimes rather bad. Fourth,

the shower data were not taken with the counters in gimbals. This last should be a small source of error. Another difficulty that was found but eliminated was the fact that interference from the ship's radio registered. By suitable shielding and insertion of capacities in the line this was stopped.

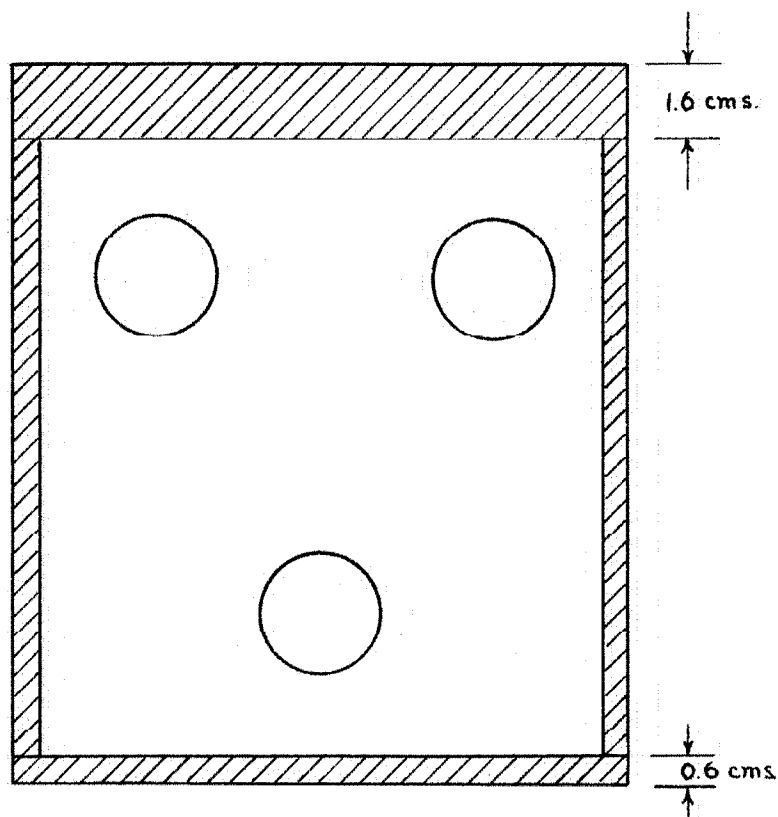


Fig. 20

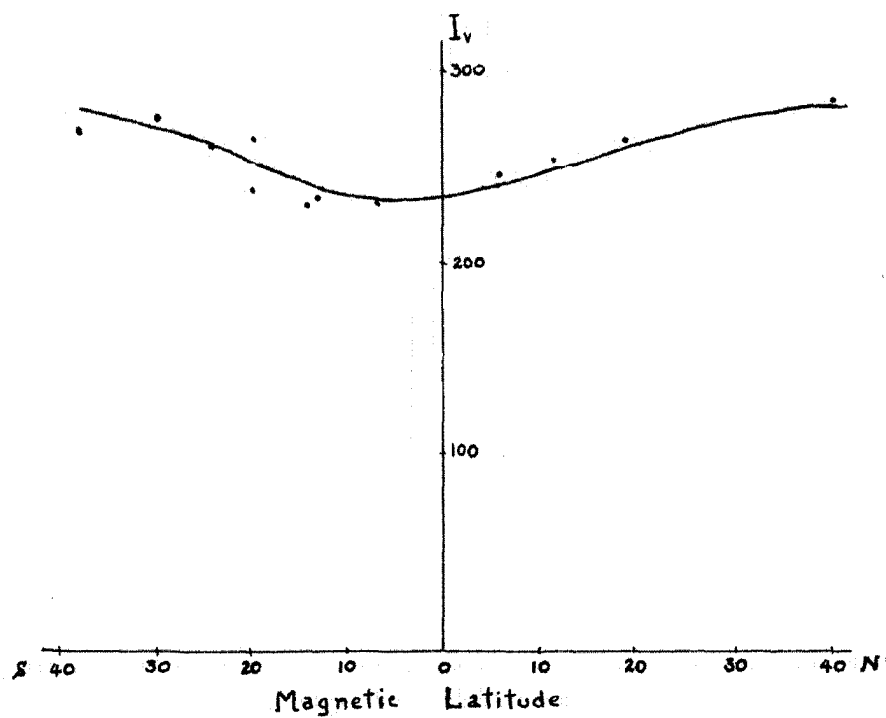


Fig. 21

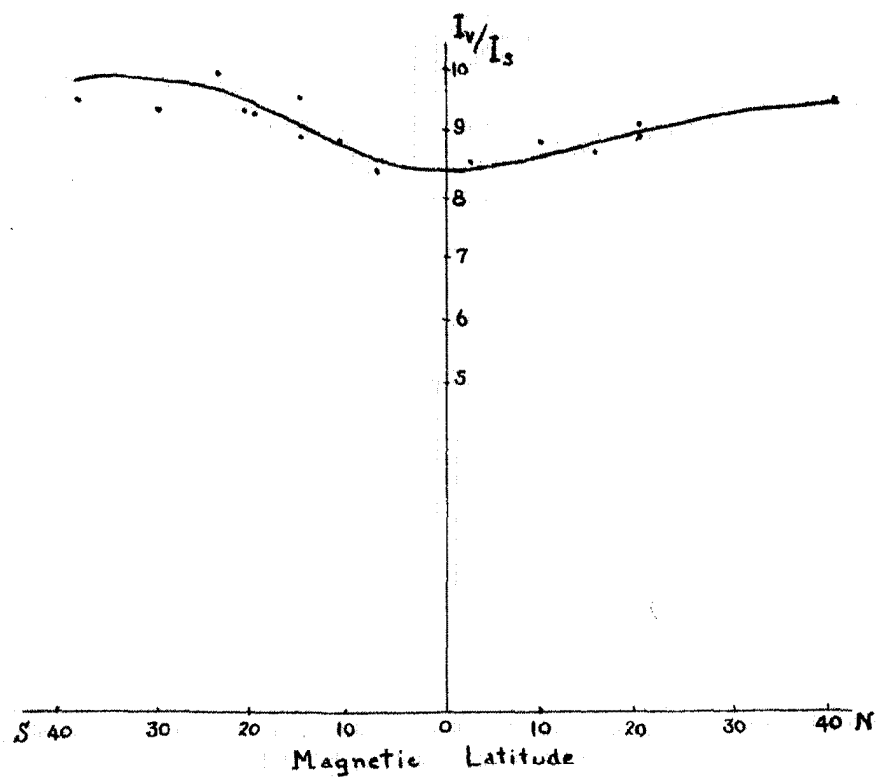


Fig. 22

In Figure 21 the data for the vertical coincidences are plotted against geomagnetic latitude. It is clear that there is a latitude effect. The amount of the effect cannot be determined accurately but it is estimated as being about 15%.

To determine whether there is a latitude effect for the showers the ratio of the vertical counting rate to the shower counting rate is used rather than the direct measures of the shower counting rates. The reason for this is that such a procedure will correct for changes in the sensitivity of the counters. If the showers show the same latitude effect as the vertical rays then this ratio will remain constant. If the ratio does not remain constant then the sign and magnitude of the change permit us to calculate the relative latitude effects for the two types of coincidence. In Figure 22 this ratio is plotted against geomagnetic latitude. It is clear that it is definitely smaller in the equatorial zone. This means that near the equator the vertical rays suffer a greater diminution than the showers. Numerically we see that near the equator the showers are relatively about 9% more numerous than in other regions. In other words the shower producing radiation is found to experience about 9% less latitude effect than the vertical rays, or about $\frac{1}{2}$ the effect that the vertical rays show.

This result may be interpreted in two ways:

(a) The showers, or at least most of the showers observed on the surface of the earth, are caused by incoming charged parti-

cles having sufficient energy to reach the earth at the equator.

(b) About half the showers are due to incoming photons, the rest arising from the same incoming charged particles that give rise to the latitude effect.

From theoretical considerations it is unlikely that the highest energy particles are more efficient in producing showers, so that the first possibility must almost certainly be discarded. Experimentally the fact that the showers increase so rapidly with altitude also shows that the highest energy particles cannot be responsible for them. It is believed that this experiment must be explained by the second hypothesis, and hence that it offers direct evidence of the presence of an incoming unionising radiation.

The above experimental result has been recently confirmed by Johnson⁽¹²⁾ who measured the showers in the Atlantic. He reported a latitude effect for the vertical rays of 20% and for the showers of 7%. He also reported that the decrease in the showers set in at a lower latitude than that in the vertical rays. This would imply that the showers were caused by the highest energy particles, but it is believed that further experimental evidence must be found before this could be confidently asserted, and in the meantime the other evidence must outweigh this one result.

These experiments are not extensive enough to enable us to get a complete picture of the nature of the primary shower producing radiation. Additional data are needed at high altitudes, and also the curve of the number of showers as a function of latitude must be found more accurately.

XI. CONCLUSIONS

The Geiger counter experiments discussed above lead to the following conclusions regarding the cosmic ray phenomena.

(i) The coincidences with the counters in a straight line are mostly caused by a single particle travelling in a straight line through the intervening matter. The evidence is not directly conclusive as to whether this penetrating radiation is corpuscular or photonic in nature. However, since the showers seem to arise from a photonic radiation it would be expected that such radiation would always give rise to secondaries distributed over a fairly wide angle. In the case of coincidences with considerable thicknesses of lead such wide angle secondaries are comparatively rare. Hence it would be more consistent with all the data to say that the coincidences under these conditions are caused in the main by a penetrating corpuscular radiation.

(ii) Perhaps 10% of the coincidences with large thicknesses of lead between the counters are caused by secondary particles making appreciable angles with the primary. These secondaries are of quite low energy.

(iii) The showers arise from the absorption of a photonic radiation that is quite readily absorbable in heavy elements. This radiation can arise from a penetrating ionising radiation, but at sea level at least half of the shower producing radiation has come in as photons from outside the earth's atmosphere.

(iv) Showers consist of sprays of gamma rays as well as particles and the type of result obtained in shower experiments depends on whether the counters are arranged to be sensitive to the gamma radiation or the particles also.

(v) An approximate analysis of the shower curves can be made and the data fitted satisfactorily. This leads to the result that the absorption of the shower producing radiation follows a mass absorption law while the shower particles are absorbed nearly according to a Z^2 law. Extrapolating the result to air the shower particles should have an absorption coefficient of about 0.5 per meter of water.

(vi) The shower producing radiation is definitely softer than the general radiation and at the same time the latitude effect for the showers is smaller. These two facts taken together rule out the possibility that the showers are a secondary phenomena from the highest energy particles and show definitely that some at least of the showers are caused by incoming photons.

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